

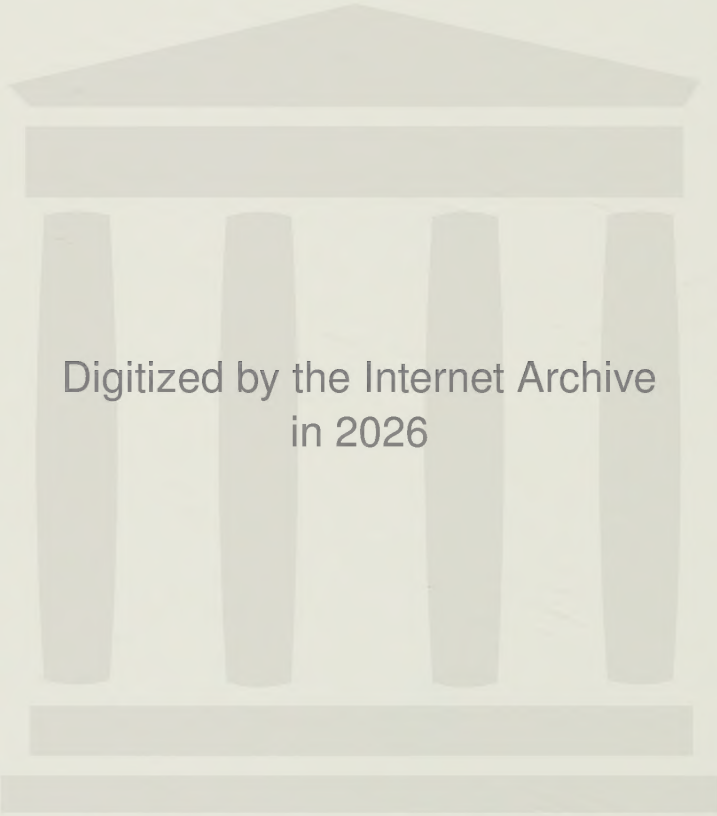
Economics of Fisheries: Some Problems of Efficiency

1974

Rögnvaldur Hannesson

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Rögnvaldur Hannesson

**ECONOMICS OF FISHERIES:
SOME PROBLEMS
OF EFFICIENCY**

Studentlitteratur

Lund, Sweden

Rögnvaldur Hannesson

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FOREWORD

Despite having been raised in a small fishing village in Iceland and, on top of that being of a fisherman's family, I would not say that I ever liked fish or fishing. It was too hard work to bring it on shore, but all right to eat--fresh. There were those, however, who felt that a week's hanging on the fence only improved the tasty flavour of a piece of cod or haddock, and the more obscure methods of curing ray I dare not disclose. No doubt a psychoanalyst would, if given enough time, succeed in having me believe that the real explanation of my choice of a thesis topic must be sought in experiences before the age of ten.

Be that as it may. This study is intended as a contribution to the plowing and harrowing of the field we call economics of fisheries. In retrospect I understand that one option would have been to cultivate some corner of the field intensively rather than trying to cover as wide an area as I have done. But it all began as an interest in the economic aspects of fisheries in general, although gradually becoming more and more focused on the North Atlantic cod and the fishing limits controversy. I wish to thank Dr. Sigfús Schopka at "Hafrannsóknarstofnunin", Reykjavík, for bringing the recent work by fishery biologists on these fisheries to my attention.

I began working on this study in the academic year of 1972--1973 during my stay at the University of British Columbia. I am grateful for having had the opportunity to spend some time at this institution, so widely known for research in fisheries biology and economics. I wish to thank especially Dr. Anthony D. Scott, Dr. Norman J. Wilimovsky and Dr. Colin Clark for their valuable suggestions and encouragement while the research was in progress. The U.B.C. also deserves credit for allowing me to use its computing facilities; in that context I must mention the personnel in the computing room at the Institute of Animal Resource Ecology who was most helpful.

Here at Lund, where the study was completed, people have been willing to read and discuss its various parts. My thanks go, first, to my supervisor, Professor Björn Thalberg, and to Anders Borglin, both of whom have taken great interest in my work. Others who at various times participated in discussion seminars and contributed valuable suggestions include Professor Bengt Höglund, Ingmar Hansson, Göte Hansson, Krister Hjalte, Lars Jonung, Bo Larsson, Karl Lidgren, Göran Skogh, Charles Stuart, Lars-Gunnar Svensson and Lars Söderström.

I wish also to thank Magister Knud P. Andersen, "Danmarks Fiskeri- og Havundersøgelser", Copenhagen, and Dr. D.J. Garrod, "Fisheries Laboratory", Lowestoft, who took the time to read through an earlier draft. Of course, nobody except myself is in any way responsible for errors that may remain.

Last but not least, I acknowledge the financial support given by the Icelandic Science Foundation. (Vísindasjóður).

Lund August 1974
Rögnvaldur Hannesson

Symbols and abbreviations

- C = Cost per unit of fishing *mortality*
c = Cost per unit of fishing *effort*
F = Fishing mortality (instantaneous)
f = Fishing effort
G = Growth function
g = Relative growth rate
H = Production function (except a "Hamiltonian" function in Ch. 2 and 5)
h = Age of fish (index)
M = Instantaneous natural mortality
N = Number of fish
P = Market price of fish
 p^S = Seller's price of fish
 p^b = Buyer's price of fish
Q = Imputed price of fish
q = Availability coefficient
R = Number of recruits
r = Social discount rate (discrete)
 t_r = Time of recruitment
 t_c = Time of recruitment to the fishery (first capture)
U = Social utility (cardinal)
V = Intra-marginal rent of fishermen
Y = Yield
Z = F+M
W = Weight of stock (or cohort)
 w_h = Weight of individual fish at age h
 $\bar{w}_h$ = Mean weight of fish during the h+1th year of age
ICES = International Council for the Exploration of the Sea
ICNAF = International Commission for the Northwest Atlantic Fisheries
MTH = Million ton-hours
TMT = Thousand metric tons
 ϵ = Gear selectivity parameter
 λ = Life-Span of fish
 ρ = Instantaneous social rate of discount
 μ, γ , multipliers
 α, β, ϕ , loci

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Chapter 1

INTRODUCTION

An early reference to the economics of fisheries is to be found in Marshall's "Principles". In discussing economies of scale he took the following hypothetical example:

"...Suppose that the disuse of meat causes a permanent distaste for it, and that an increased demand for fish continues long enough to enable the forces by which its supply is governed to work out their action fully..... The source of the supply in the sea might perhaps show signs of exhaustion, and the fishermen might have to resort to more distant coasts and to deeper waters, Nature giving a Diminishing Return to the increased application of capital and labour of a given order of efficiency. On the other hand, those might turn out to be right who think that man is responsible for but a very small part of the destruction of fish that is constantly going on; and in that case a boat starting with equally good appliances and an equally efficient crew would be likely to get nearly as good a haul after the increase in the total volume of the fishing trade as before. In any case the normal cost of equipping a good boat with an efficient crew would certainly be no higher, and probably be a little lower after the trade had settled down to its now increased dimensions than before. For since fishermen require only trained aptitudes, and not any exceptional natural qualities, their number could be increased in less than a generation to almost any extent that was necessary to meet the demand; while the industries connected with building boats, making nets, etc. being now on a larger scale would be organized more thoroughly and economically. If therefore the waters of the sea showed no signs of depletion of fish, an increased supply could be produced at a lower price after a time sufficiently long to enable the normal action of economic causes to work itself out: and, the term Normal being taken to refer to a long period of time, the normal price of fish would decrease with an increase in demand."¹

Fisheries have developed rapidly since the days of Alfred Marshall. The total world catch of fish has increased many times over; only in the period since 1950 from 20 to almost 70 million metric tons. Nevertheless, few contemporary economists would expect a falling supply price of fish as demand increases, owing to economies of scale. The increase in yield has been due to fishermen's resorting to more distant waters and to "new", previously unexploited species. In many fish stocks there are abundant signs that man is

1 A. Marshall: Principles of Economics, Ninth (Variorum) Ed. The MacMillan Company, New York 1961; pp. 370--371.

responsible for the largest part of the destruction of adult fish that is constantly going on, and that Nature gives a diminishing return to fishing effort in the long run. The supply curve of fish from a given stock is indeed backward bending (cf. Copes 1970), as in other cases of limited capacity (e.g. bridges, roads). The supply price of fish would therefore be expected to *rise* and not to fall as demand increases.

The problems in which we shall be interested here have to do with optimal exploitation of fish stocks, explicitly considering the biological production constraint. Will market prices give correct signals to profit maximizing, competitive fishermen? Is the prevailing institutional arrangement in fisheries adequate to achieve efficient exploitation? Besides considering these questions in a general context we shall take a closer look at the North Atlantic cod fisheries.

Natural resources are often classified according to whether they are replenishable or not. This appears to be a relevant distinction. The exploitation of a non-replenishable resource implies depletion; determining the optimal rate of extraction involves choices such as "how much to leave to unborn generations", or "when comes the day of ultimate depletion". The exploitation of a replenishable resource gives us a different choice; the rate of extraction may be adjusted to the rate of replenishment so that the resource is never depleted but is an asset with a given yield per unit of time.

This classification is not unambiguous however. Most, if not all, natural resources are capable of replenishing themselves once a long enough view is taken. This is true even of minerals and oil, but their rate of replenishment is so low as to be irrelevant; our utilization of these resources would be practically nil if it were adapted to the rate of formation of new oil or minerals in the earth's crust. The argument that our present rate of extraction of these resources implies lack of concern for unborn generations is familiar, but may be viewed as an argument about the appropriate social rate of discount. If the net value of a given stock of a natural resource is growing at a rate that is less than the discount rate, it ought to be depleted as long as the marginal social revenue of extraction exceeds marginal social cost.

Is it possible, then, that some natural resources which we without hesitation would regard as replenishable, such as some forests and whale stocks, ought in fact to be depleted, because of their low rate of growth? The idea may appear outrageous, and we do not deny the legitimacy of "option demand" for whales as an irreplaceable part of our fauna or forests as objects of beauty, but the example illustrates that it *may* be desirable to deplete stocks of replenishable natural resources.

Deliberations of this kind clearly presuppose that "somebody" is calculating and planning the extractive industry, or else that private individuals or firms are pursuing their own objectives, given price signals from the market, in such a way that the resulting allocation of resources is optimal. This is precisely the point where the institutional arrangement prevailing in world fisheries is notoriously deficient, encouraging depletion of fish stocks. In most cases fish do not become anyone's property until captured, which of course breeds a strong incentive to do so as quickly as possible. The reproductive capacity of a given fish stock is therefore not the property of individuals or firms and cannot be bought and sold on a market, and its use will therefore not be limited by the market although it is a scarce resource. Private fishermen, or fishing firms, in competition thus have an interest to grab as much as they can at any given time without paying any attention to the relation between stock size and its rate of replenishment. Extinction will be prohibited only to the extent that it will be uneconomic to deplete stocks beyond their lowest viable level.

Thus a competitive fisherman would regard the fish stock as being outside his control. As far as the stock size is important for the profitability of the fishery this will give rise to external diseconomies, or "*stock-externalities*". A competitive fisherman (fishing firm) may be expected to identify his marginal product with the amount of fish extracted by "a unit" of factors of production engaged in the fishery. Equilibrium would then obtain in the fishery when the value of a "representative" fisherman's (firm's) marginal product is equal to his incomes forgone by a marginal transfer of resources to the fishery. But the problem is that a fisherman's (firm's) private marginal product is not equal to his marginal social product, as each single fisherman (firm) causes some external diseconomy to the fishery as a whole by affecting the size of the stock. Two effects may be distinguished: first, reducing the stock will affect the rate of growth of the fish population and, second, it will make it more costly to extract a given weight of fish. The common property fishery will therefore be characterized by an equality between the value of fishermen's *average* product and their opportunity cost rather than the value of their *marginal social* product and their opportunity cost.

To our knowledge, the first economist to consider the problems of resource allocation arising from stock-externalities was the Danish economist Jens Warming (1911, 1931). Later but independently of his work similar and more comprehensive analysis by Gordon (1954) and Scott (1955) appeared in the English speaking literature. These pioneers and most followers treated the

problem of optimal resource allocation in fisheries as a choice between stationary states, contrasting the optimal stationary state with the equilibrium in the industry. The transition from an initial position to the optimum stationary state was usually ignored as if it did not matter, but recently Clark (1973a) has pointed out that this amounts to no discounting of future benefits, and that the rate of discount may significantly affect which stationary state is optimal. In Chapter 2 we shall begin by reviewing the theory of exploitation of a common property resource.

The early analysis suggested that equilibrium in a common property fishery would be characterized by fishing effort in excess of optimum (Warming 1911, 1931, Gordon 1954, Scott 1955). The qualitative dynamics that have recently been added to the comparative static analysis have pointed out the possibility of species extinction as a result of commercial fishing (Smith 1968, 1969, Quirk and Smith 1970, Gould 1972, Southey 1972). Chapter 2 contains a contribution to this analysis. The likelihood of extinction is discussed in terms that are familiar to the fishery biologist, explicitly referring to the growth rate of biomass and the availability of fish. It is shown that (unstable) equilibria in a common property fishery may imply small yields being taken by *small* fishing effort rather than an excessively large one.

As externalities arising from the absence of property rights are such an important characteristics of marine fisheries, the Pigovian theory of corrective taxes is particularly relevant for this industry. Besides the externalities that we have described above and labelled "stock-externalities" a number of other externalities may arise; e.g. from congestion or the use of gear that does not discriminate between "old" and "young" fish in an optimal way. Smith (1969) has considered how these three externalities can be simultaneously corrected by a suitable mixture of fees and taxes. We shall only be concerned here with stock externalities; in Chapter 3 we discuss Pigovian taxes as corrective devices for such externalities. As long as a given stock of some species is considered in isolation the corrective tax is always in one direction, depressing the price of fish encountered by fishermen in the marketplace in order to lower the value of the marginal fisherman's private product and make it equal to his social product. As soon as interdependence of species is accounted for the problem becomes much more complicated. One species must then be regarded as "input" into the production of another and some price be imputed to it in this capacity. The Pigovian tax may then cut either way; the exploitation of a species that competes with the fishery in "harvesting" some other species of fish should in some cases be subsidized,

and changes in the relative price of two species may give an entirely false signal as to in which direction to alter the allocation of fishing effort to the two species.

Having established the general, theoretical framework we turn to consider the problem of optimal fishing in a more applied context. The North Atlantic cod fisheries have a long history and are of major significance in world fisheries. The nations taking part in these fisheries have established a long record of cooperation on scientific research and data gathering, but less so on management. Recently two comprehensive reports by fishery biologists on the North Atlantic cod stocks have been published, but the economics of these fisheries are less well examined. It is our purpose here to deal with the question of efficiency in the North Atlantic cod fisheries at a fairly general level, on the basis of these recent biological investigations (Clayden 1972, Anon. 1972). The questions we shall attempt to answer concern excessive exploitation, and whether each fish stock should be managed as an independent unit or the whole area harvested by distant water fleets rotating between stocks.

In the first part of Chapter 4 we introduce the reader to the Beverton-Holt yield model, which has been widely and successfully applied to the North Atlantic cod fisheries by fishery biologists, and proceed after that to the question of efficiency. As the North Atlantic cod stocks have been common property to which access has been free for any fisherman, one would expect to find inefficient exploitation, probably to the extent that a permanent reduction of fleet capacity would improve sustained yields. This hypothesis of inefficiency is examined by calculating the optimum stationary rate of fishing for various assumptions of fishing costs and time preference and compare it to the recent rate of exploitation. The results are presented area by area in Chapter 4; in all cases inefficient exploitation is indicated.

The concept of stationary state is time-honoured in the literature on common property fisheries. Valuable insights into the problems accompanying the common property regime have been obtained by analyzing alternative stationary states. However, restricting the analysis to stationary states glosses over some aspects which may be crucial in fisheries. Notwithstanding price fluctuations, any bionomic (biological + economic) equilibrium is continuously upset by exogenous fluctuations in the growth rate, which in the case of cod are of a large magnitude. The most relevant problems to study are therefore perhaps those connected with dynamics proper; i.e. how to vary the rate of fishing over time. These aspects have recently received attention; Clark et al. (1973) have examined optimal dynamics in the Beverton-Holt

model. We begin Chapter 5 by reviewing this contribution and drawing attention to peculiarities connected with some technological features specific to fisheries; the imperfect control over the resource to be harvested leads to the unexpected result that, given non-zero costs, a higher discount rate implies a prolonged period of harvesting a given "crop", rather than simply advancing the start of the harvesting season.

The advantage of variable fishing intensity in a multi-cohort fishery is considered by simulating a Beverton-Holt model of the cod stock at Iceland. It may appear unduly restrictive to consider only one stock of a certain species of fish, but this approach is nevertheless in some respects more instructive than a general, associative model. The loss in generality is compensated by a gain in validity, and the results obtained with respect to one specific stock are instructive with regard to the exploitation of other stocks with similar characteristics. A general associative model may tell us to decrease fishing if the value of its marginal product is below its cost, but it tells us nothing about the absolute level of fishing that may be desirable, how much it should be decreased, or about the transitory stage. A mechanistic yield model tells us all this and rewards us with meaningful policy conclusions, to the extent that it reflects reality with an acceptable degree of accuracy.

The last part of Chapter 5 recognizes that variable harvesting of the North Atlantic cod would involve a rotating fishery, concentrating on one or a few areas at a time while leaving others to recover, and speculates on the profitability of this arrangement compared to managing each stock as an isolated unit.

Fish stocks are not unique in being common property, so are even natural resources such as water, air etc., which frequently are excessively used as well. It is often possible for a group of individuals to optimize the use of common property resources collectively, more often than not through the political institutions of the state. But the common property problem sometimes has an international dimension; this is true for fish in particular. Fisheries frequently take place in the common part of the oceans, outside the jurisdiction of national states, where exploitation is free for all at the present time. In cases like that there is no political institution to deal with the problem of excessive exploitation. In some cases the nations directly concerned have made *ad hoc* agreements to manage the fisheries; in other cases coastal states have extended their jurisdiction unilaterally in order to appropriate fish stocks. An international attempt is now being made to establish international law on these matters, where two opposing lines of

thought may be distinguished. Some have suggested that an international organization to manage world fisheries be created, while others favour extending the fishing limits of coastal states. We shall consider this question in Chapter 6, which is also the last one except for a short conclusion.

Chapter 2

THE ECONOMIC THEORY OF SINGLE-SPECIES FISHERIES

2.1. Introduction

In this chapter we shall be concerned with some general aspects of single-species fisheries; that is, ecological links between species will not be considered explicitly, and only one species is assumed to be fished without any interference by other species. We shall consider the exploitation of a unit stock of fish in isolation; by "unit stock" we mean the biomass of a given species which is contained within certain geographical limits and does not interact with other fish of the same species outside those limits. The main emphasis will be on examining the biological limits to production and the properties of social optimum vs equilibrium in the fishing industry. In this context the principles of the economic theory of single-species fisheries will be reviewed, and some concepts that are used widely throughout this study will be introduced.

We begin by considering the growth rate of a fish stock as a function of the stock itself and how fishery biologists have approached this relation in empirical work. This stock-growth relationship makes it relevant to regard the stock as a "factor of production", to which is added that it is easier to recover a given quantity of fish from a large (dense) stock than a small one. A fish left in the sea will therefore have a shadow price as an input into the production of fish, and an external diseconomy will prevail in the fishery if fishermen do not reckon with that price. The divergence between social optimum and equilibrium in the industry is studied by comparing optimum and equilibrium stationary states. The probability of extinction of species as a result of fishing is examined by analyzing how the relative growth rate of stock and fleet efficiency (availability of fish) may be affected by changes in stock density. It will be shown that a low relative growth rate of heavily exploited stocks together with unchanged (or increased) availability will imply a greatly increased risk of extinction. This chapter concludes with a review on the impact of discounting on optimum stationary states.

2.2 Growth and Sustainable Yield

Fish like any other living organism is a replenishable resource. Anyone is sufficiently familiar with animal husbandry to know that a careful attention together with stable external conditions may sustain a stock of animals and its yield for a very long time. Yields from fish stocks may also be sustained; there are records of fisheries which have been going on for cen-

turies without being depleted. As most fisheries are still in the hunting stage, however advanced, and the existence of virgin state equilibrium requires zero average growth of an unexploited stock, this ability of fish stocks to sustain fisheries over long periods is to be explained by an increase in natural growth generating surplus production that is capable of sustaining the fishery without depleting the stock to extinction. Increased predation through fishing will initially reduce the stock at which it is aimed, but the depletion may be brought to a halt by an increase in the relative growth rate in response to the reduction of stock and a new equilibrium situation attained where the rate of decrease through fishing will equal the rate of increase through natural growth.

Thus we are led to consider the natural growth of a fish stock as a function of the stock itself (W). Denoting natural growth rate, net of natural deaths, by $G(W)$, we have *in absence of fishing*

$$(2.1) \quad \dot{W} = G(W).$$

The stability of virgin state equilibrium requires that the natural growth rate be positive for lower and negative for higher stock levels in the neighborhood of that equilibrium. Since no fish produce no fish and few fish produce little in absolute terms at least, it follows that the growth rate of stock rises as the stock increases from a low level, reaches a maximum at some intermediate level, and falls as it grows toward virgin state equilibrium level. Three qualitatively different growth curves which are compatible with these assumptions are shown in Fig. 2.1 a--c. In all cases there are two possible equilibrium stock levels with no fishing: the virgin level, W' , which is stable, and a lower level, W'' , which is unstable. This lower level is equal to zero in Fig. 2.1 a and c, but not in b. Whenever $W'' > 0$ this implies

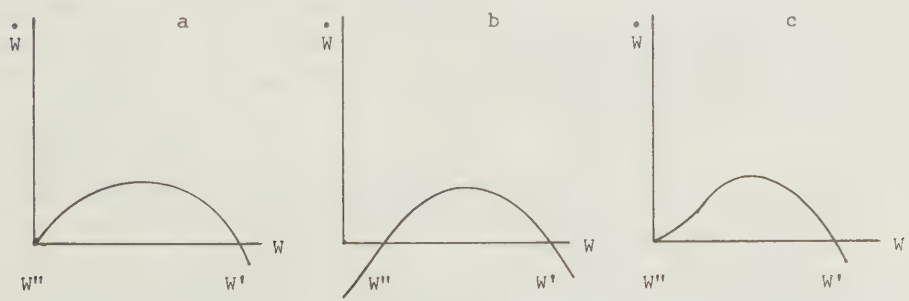


Fig. 2.1

that a minimum level, W'' , is required for the species to be viable. If the stock falls below this critical level, it will be driven to extinction.

If a fishery starts to exploit a virgin stock, it will pass through an initial phase of extraordinarily good catches, at least in relation to fishing effort, as the stock is being reduced to a new equilibrium level. In fisheries that have been going on for a long time this initial "good old days" phase is lost long back in history and may also have been spread over a long period of time as fishing technology and effort gradually developed. In fisheries that have been opened up only recently this initial phase is quite distinct, due to the potential for intensive exploitation offered by modern technology. In the long run, however, the reproductive potential of each stock sets definite limits to production. One way of taking account of these limits is to assume that the optimum exploitation of the fish stock involves choosing the best of all attainable stationary states, in which a stationary stock sustains a stationary flow of yield *ad infinitum*. This is what usually is meant by *sustained*, or *sustainable*, yield. The optimum stationary state may then be compared to the equilibrium position that the fishery might attain. This simplifies the analysis in that only stationary states need be considered, and the growth function can be regarded as a long term production possibility frontier, which must be estimated for further analysis.

2.3. Applied Yield Models

Fishery biologists have developed two approaches to estimate growth, or stationary yield functions, of fish stocks, the Schaefer approach (Schaefer 1954) and the Beverton-Holt approach (Beverton and Holt 1957).¹ The difference between the two approaches is best explained by referring to the causal factors behind the surplus production yielded by stock levels below virgin state equilibrium. First, decreasing the stock may mitigate the competition for a given supply of food, which would be expected to increase the growth rate of each fish and perhaps also lower the natural mortality. Second, the number of young fish recruited to the stock may -- within certain limits -- be inversely related to the size of the spawning stock, as older fish often prey on younger fish of the same species; this effect will be reduced by fishing as it increases the mortality risk for adult fish and lowers the mean age of the population. But, third, the effect of fishing on the age structure of the population is in itself a sufficient explanation of the fact that exploited

¹ The two approaches are explained and compared in an article by Beverton and Schaefer: "Fishery Dynamics: Their Analysis and Interpretation", in *The Sea*, Vol. 2, pp. 464--483, ed. M.N. Hill.

fish stocks are capable of yielding some surplus production. Increased fishing mortality will always have the following opposite effects on the natural growth rate, besides affecting food competition and predation on young fish: (i) it reduces the number of fish, which in turn tends to decrease the natural growth rate as there will be fewer fish growing, and (ii) it reduces the mean age of the population, which means that young, fast growing cohorts of fish that add more to their weight through individual growth than they lose through natural mortality will become more dominant in the population. The latter effect will be dominant when exploitation is increased from a "low" level; a further reduction of the mean age will then increase the rate of growth of the whole population. As fishing mortality is increased beyond a certain level the first effect will become dominant, and thus there exists a dome-shaped growth curve, relating the rate of growth to the size of the stock. The Beverton-Holt approach concentrates on this effect of fishing on lowering the mean age and reducing the number of fish, ignoring environmental effects such as competition for food and predation. In the simple Beverton-Holt model the growth rate is a function of the age composition of the stock, but as long as each stock level corresponds to a unique age composition, which is true under stationary conditions, the growth rate is in effect a function of stock. If then the growth parameters of an average fish are known, it is possible to compute the stationary yield resulting from any given level of fishing by analyzing its effect on the stationary size and age composition of the fish population. We shall return to this in Chapter 4.

The Schaefer approach on the other hand does not rely on an identification of the causal factors behind the surplus production. It assumes a general growth function (Eq. 2.1), often written

$$(2.1') \quad \dot{W} = g(W) \cdot W,$$

where $g(W)$ is the *relative* natural growth rate, net of natural deaths. Equation (2.1') holds in *absence of fishing*, otherwise the predation caused by fishing must be subtracted on the right side. In applied studies it is necessary to specify the functional form of $g(W)$; frequently the Verhulst-Pearl logistic function

$$g(W) = k \cdot (W_{\infty} - W), \quad k \text{ and } W_{\infty} \text{ constants,}$$

is used. This results in a growth function involving W raised to the second power (Fig. 2.1 a) and implies that the relative growth rate, $g(W)$, is a monotonically decreasing function of stock. However, the stability of virgin state equilibrium requires only that this be true in the neighborhood of that equilibrium, whereas it need not be true for "low" stock levels; cf. Fig.

2.1 b--c, where the relative growth rate is an increasing function of stock for "small" W . It will be shown in section 2.6 that it is of crucial importance whether or not the relative growth rate is a monotonically decreasing function of stock for all $W > 0$.

Thus the difference between the two approaches is to some extent that the Schaefer approach is more general, while the Beverton-Holt approach attempts to explain the sustainable yield by specifying its most crucial determinants at the loss of ignoring others. In this and the next chapter we shall proceed in the spirit of the Schaefer approach, but without further specifying the growth function, as we shall be concerned with fairly general characteristics of fisheries and not with any specific fishery. In the more applied part of this study we shall follow the Beverton-Holt approach, as it is suitable for cod fisheries, with which we shall be concerned. It would be wrong, however, to give the impression that the Schaefer approach is less "applicable" than the Beverton-Holt approach. It is possible to estimate the parameters of a specified function $g(W)$ if sufficient data are available, and the Schaefer approach has indeed been applied to a number of fisheries. Circumstances would largely dictate which one of the two approaches would be followed in an applied study. The Beverton-Holt approach requires estimates of growth parameters, which are not easily obtained for all species. Its application is most reliable when fishing effort does not vary widely over time and environmental factors thus likely to be constant. Furthermore, it is indispensable for studying the effects of measures affecting the age of fish selected by the gear, e.g. mesh regulation. The Schaefer approach requires data of fisheries that have varied considerably over time, since it is necessary to have data on alternative stationary states in order to estimate the growth function. The requirement that the data in fact refer to stationary conditions may be relaxed, as the method has been modified to apply to situations when the population is in a stage of transition.¹

2.4. The Production Function of a Fishery

In order to be able to use the tools of economic analysis it is necessary to define a production function that relates the yield to some measure of inputs. We shall make the conventional simplifying assumption that the fish are caught by a composite factor of production, labelled "fishing effort". This effectively ignores the possibility of non-homogeneous fleets and avoids the problem of determining optimal fleet composition. It is by

¹ Applications of the Schaefer approach are extensively discussed by Ricker (1958).

no means alleged that this is an unimportant problem; non-homogeneous fleets need not be "historical accidents", owing to technological progress and obsolescence, but since we are interested here in more general aspects of optimal exploitation in fisheries we choose to disregard it.

The production function of the fishery will be defined as follows:

$$(2.2) \quad Y = q(W, f) \cdot f \cdot W$$

where Y and f denote yield and fishing effort respectively, whereas q is the *availability coefficient*, expressing the yield per unit of effort (Y/f) as a fraction of the biomass to which fishing effort is applied. It may be regarded generally as a function of both fishing effort and biomass.

It is often assumed that the availability coefficient is a constant, independent of fishing effort and stock. This would be true, if fishing effort is directly proportional to the probability that a fish will be entrapped by the fishing gear. In applied studies fishery biologists attempt to find a measure of effort which meets this requirement. The biologist's preferred definition of fishing effort per unit of time is therefore the number of units of standard gear kept in or hauled through the water. The mortality risk for each fish in a population which is uniformly distributed in the area being fished is then directly proportional to fishing effort. That measure of effort which is directly proportional to the mortality risk facing each fish is sometimes referred to as *effective fishing effort*. From the economist's point of view this definition is not quite satisfactory, as it ignores any effort necessary for transportation, search and preliminary processing at sea. We shall nevertheless proceed initially on the assumption of a constant availability coefficient. The yield from a given level of fishing effort but for variable stock of fish is then a straight line from the origin; a family of such lines is shown in Fig. 2.2 a, together with the growth curve from Fig. 2.1 a. As the point of intersection between the growth curve and a constant-effort yield line represents a stationary state, it in fact represents one point on the sustainable yield curve; that is, the stationary flow of yield that would result from a sustained level of fishing effort. By successively changing fishing effort one may imagine tracing out the sustainable yield curve in Y, f space. This curve is shown in part b of Fig. 2.2. Note that a higher stationary effort implies a lower stationary level of stock and vice versa.

2.5. Bionomic Equilibrium and Social Optimum

To make the analysis as simple as possible without invalidating the main arguments, let us assume that the price of fish is a constant, invariant with time and the quantity supplied. This makes it possible to interpret the yield

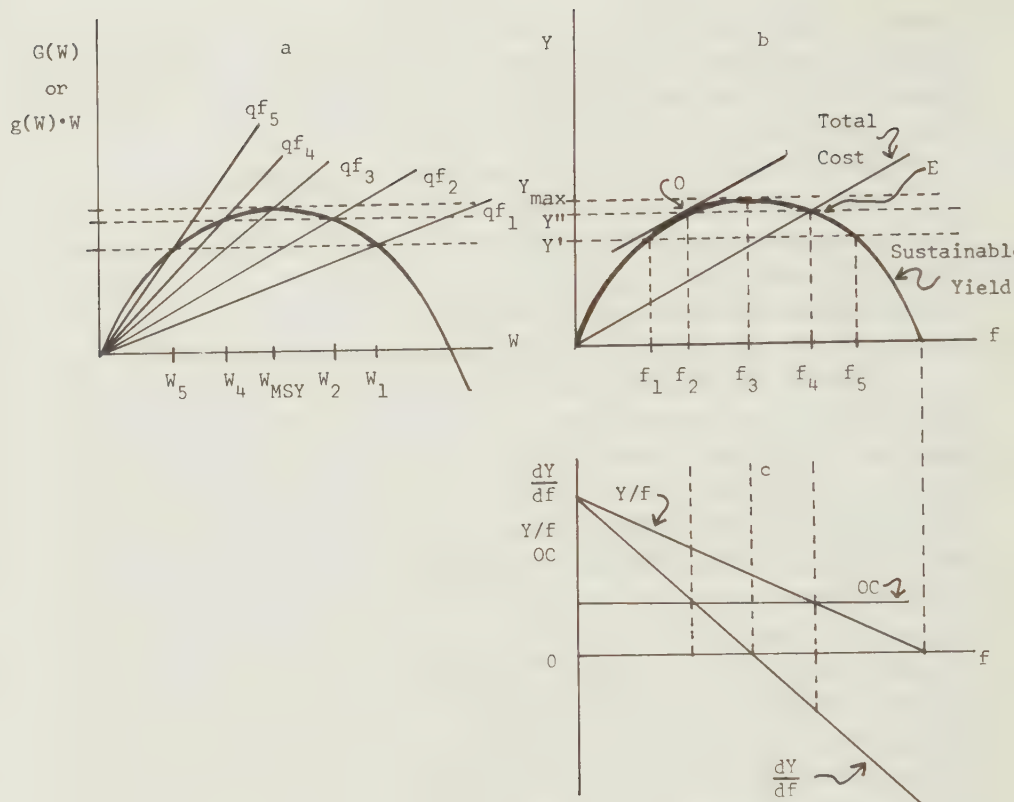


Fig. 2.2

curve directly in monetary terms, implicitly setting the price of fish equal to one. Allowing for a downward-sloping demand curve makes the geometry more complicated and may cause multiple equilibria (cf. Anderson 1973). We shall further assume that fishermen and fishing fleets are homogeneous and that employment opportunities elsewhere in the economy are not affected by the size of the fishery, so that the opportunity cost of fishing effort is constant. Hence, the cost curve is a straight line with a positive slope, beginning at the origin. This is sufficient for our purposes; although variations in skills among fishermen is a well known fact of life, it has a bearing on the distribution of income among them and the division of labor in the economy, but is qualitatively of less importance for the optimal level of effort and bionomic equilibrium (cf. however Turvey 1964 and Copes 1973).

When access is free to fish stocks and no one is able to impose fees for their exploitation, the only cost incurred by fishermen will be their in-

comes forgone in the best alternative occupation together with running and maintenance costs of their boats; in short, the opportunity cost of fishing effort. Fishermen may then be expected to enter (leave) the fishery as long as the value of the catch per unit of effort is greater (less) than the opportunity cost of effort, since the difference between the value of the catch per unit of effort and the opportunity cost of effort represents over-normal profit (loss) and no fisherman has any reason to expect that he will do better or worse than others as long as we ignore differences in skills.¹ Equilibrium in the fishery therefore requires that total revenue equals total cost of fishing. Long run equilibrium in the fishery implies biological equilibrium as well; i.e. that the stock has attained a stationary level, and that the stationary flow of yield is equal in value to the opportunity cost of obtaining that yield. In Fig. 2.2 b such equilibrium occurs at point E, where the total cost line intersects the sustainable yield curve. The term "bionomic equilibrium" has become established for this simultaneous equilibrium in the economic and the biological systems (Gordon 1954).

As Warming (1911) observed, fishermen's opportunity cost will in the long run tend to be equal to the average revenue in the fishery. In part c of Fig. 2.2 we have plotted marginal cost (OC), marginal stationary revenue (dY/df) and average stationary revenue (Y/f) (note that we use fish as a numeraire). The long term equilibrium is at point E, or where $OC=Y/f$. In this case it is possible to make the collective of fishermen better off in the long run by reducing fishing effort, since that would increase sustained yield. The stationary flow of profits is maximized at point O, where the stationary marginal revenue is equal to fishermen's opportunity cost.

If the opportunity cost of fishermen represents the social value which their labor and capital produces in the best alternative use, and, furthermore, if the price of fish represents the social value of a marginal unit of that commodity, the intertemporal maximization of social welfare is equivalent to maximizing profits in the fishery. In the absence of discounting this is equivalent to maximizing the stationary flow of profits, since it will always in the long run prevail over whatever short term losses that might be incurred to attain the stationary state which maximizes the stationary flow of profits. In that case the social optimum and the maximum of total profits coincide at point O, as a marginal unit of effort produces the same social

1 Nothing will be altered by substituting the word "fishing firm" for "fisherman", if the reader prefers. Expansion of fishing effort may occur through expansion of existing firms as well as entry by new firms.

value in the fishery as in its best alternative use. As a sole owner with an infinite albeit transferable right to tenure of the fish stock would be able to appropriate that profit, maximization of Ricardian rent in the fishery is equivalent to maximizing social welfare.

We may now substantiate a little better our assertion in the introductory chapter that a competitive fisherman's private marginal product would always be less than his marginal social product. The assumption of homogeneity implies that a fisherman's private marginal product is equal to the average product in the fishery, while we may interpret the change in stationary yield resulting from a permanent marginal change in fishing effort (dY/df in Fig. 2.2) as his marginal social product. This divergence between private and social values is caused by the lack of incentives for competitive fishermen to take account of their impact on equilibrium stock size and thereby stationary yield (growth) and the cost per pound fished. A fisherman who abstains from fishing will by his abstention produce some benefits for those who are engaged in the fishery as the equilibrium stock will then be greater than otherwise; therefore it will be cheaper to recover a given quantity of fish and the stationary yield may even be increased. Yet these benefits are shared only by those who are engaged in the fishery, and, it may be added, society at large, whereas abstention would clearly be a sacrifice for the competitive fisherman as long as his prospective share of the total catch is of greater value than his incomes forgone by fishing.

As an example, let us consider the stationary yield Y in Fig. 2.2, which happens to be both the optimum and equilibrium yield in the fishery, depending on whether it is taken by the "small" effort f_2 or the "large" effort f_4 . In stationary terms it is clearly preferable to use the combination small effort--large stock, but in that case there are overnormal profits to be made in the fishery, and prospective fishermen will find it profitable to enter until the equilibrium situation (E) has been attained.

We have argued that stock externalities in a common property fishery will lead to inoptimal allocation of resources. There may even be additional causes of divergence between private and social values in the fishery; e.g. congestion on the fishing grounds. Second-best problems may to some extent lessen this divergence, but only by some extraordinary coincidence would the bionomic equilibrium coincide with social optimum. Discounting of future benefits will also diminish the divergence between private and social marginal product, defined in terms of stationary yield. We shall consider the impact of discounting on the choice of stationary state in the last section of this chapter.

One additional aspect of inoptimal allocation of resources in common property fisheries is worth mentioning, also discussed by Warming (1911). The allocation of fishing effort between fishing grounds of different qualities will be inoptimal, as the superior ground attracts too many fishermen. Fig. 2.3 shows the marginal revenue (MR), average revenue (AR) and opportunity cost (OC) on two grounds of different qualities. In bionomic equilibrium the superior ground (A) will be excessively exploited vis-à-vis the other ground (B), as it would be possible to increase total output by transferring some fishermen from ground A to ground B.

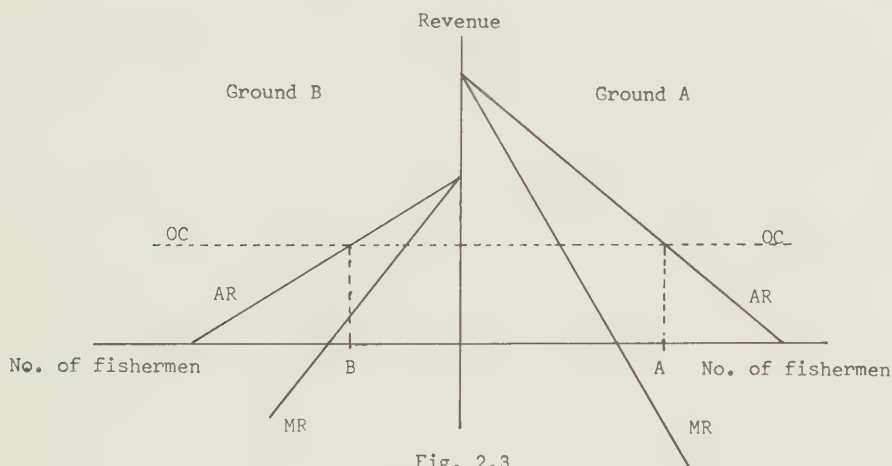


Fig. 2.3

2.6. Backward-Bending Yield Curves¹

In the preceding section it was concluded that free access to the fishing grounds would result in excessive exploitation, because, to a competitive fisherman, a fish left uncaught is a fish wasted. The fact that extermination of fish stocks nevertheless seldom occurs is to be ascribed to a rising cost of a given quantity fished as the exploited stock is depleted. Therefore, it is not profitable to catch the very last fish, and extermination is avoided if a viable equilibrium may be established with a stock no larger than the smallest size that can be exploited without a loss. But the process of extinction is a disequilibrium and not an equilibrium phenomenon. Extremely low short run fishing costs together with "unfortunate" growth functions, to be discussed below, might generate paths that lead to extinction. We shall

¹ The substance of the analysis in this section has been published elsewhere (Hannesson 1974).

in this section deduce yield curves that bend backwards instead of having a regular dome-shape and argue that fish stocks giving rise to such yield curves will face a greater risk of extinction than others. "Unusual" equilibria may also occur in fisheries connected with such stocks, involving low catches per unit of effort taken by *small* and not excessively large equilibrium fishing effort exploiting an unproductive stock. It will be argued that backward-bending yield curves are more likely to be caused by certain properties of the growth function than the production function in the fishery.

2.6.1. A Derivation of the Stationary Yield Curve

Under stationary conditions, a locus, ϕ , may be defined, tracing all relevant combinations of stock and fishing effort, by subtracting Eq. 2.2 from Eq. 2.1' and setting the result equal to zero

$$(2.3) \quad \phi(W, f) = (g(W) - q(W, f) \cdot f) \cdot W = 0.$$

Differentiation yields

$$(2.4) \quad \frac{dW}{df} = \frac{q + (\partial q / \partial f) \cdot f}{\partial g / \partial W - (\partial q / \partial W) \cdot f}$$

which shows the slope of locus ϕ in W, f space.

Let us proceed, initially, on the assumption that the availability coefficient (q) is independent of both W and f , deferring the discussion of to what extent this will affect our conclusions until later.

Equation (2.4) then simplifies to

$$(2.4') \quad \frac{dW}{df} = \frac{q}{\partial g / \partial W}.$$

It is now possible to transfer the stationary production possibility frontier to a space with dimensions Y (yield per unit of time) and f (fishing effort) by the aid of a simple geometric analysis. In Fig. 2.4 the growth curve is shown in the NW-quadrant. The locus ϕ is shown in the NE-quadrant; what is particularly important is its slope, which by Eq. (2.4') is seen to be determined by $\partial g / \partial W$. Therefore, if the relative natural growth rate is a monotonically decreasing function of W , as in Fig. 2.4 a, the slope of locus ϕ will be negative everywhere. In the special case of the Verhulst-Pearl logistic growth function ($g = k(W_{\infty} - W)$), the slope of locus ϕ will be a constant, i.e. $\partial g / \partial W = -k$.

On the other hand, if the relative growth rate is an increasing function of W as the case is in Fig. 2.4 b for $W < W^*$, the slope of locus ϕ will be positive for $W < W^*$. As $W \rightarrow W^*$ we have that $\partial g / \partial W \rightarrow 0$ and $dW/df \rightarrow \infty$. The locus ϕ will therefore have the shape shown in Fig. 2.4 b.

The SE-quadrant is merely a transformation of axis. As $Y = g(W) \cdot W$ under stationary conditions, it is a straightforward exercise to plot the

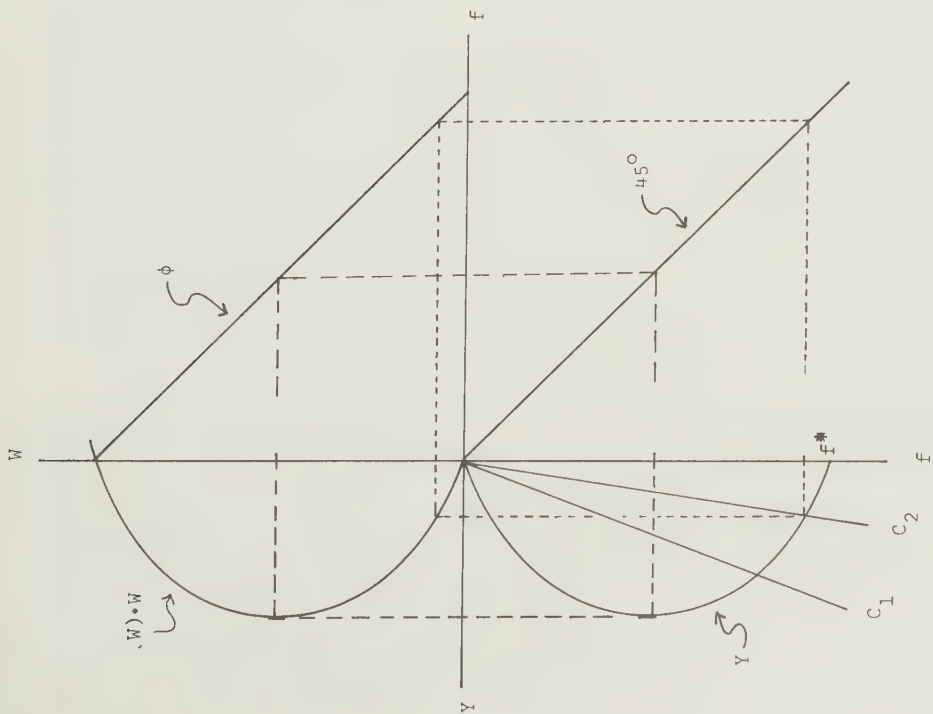


Fig. 2.4 a

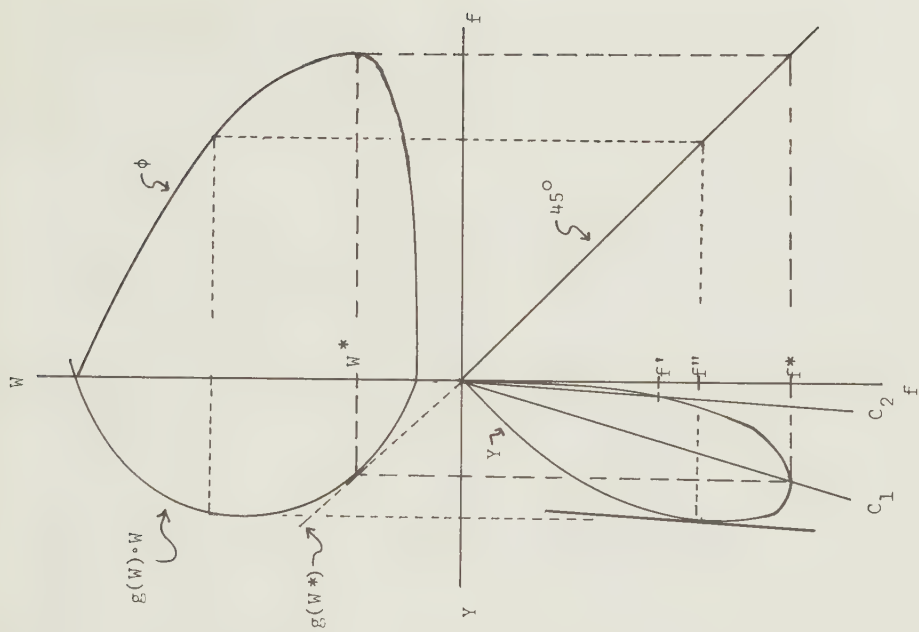


Fig. 2.4b

sustainable yield curve in the SW-quadrant. It turns out that the shape of the growth curve is of critical importance for the shape of the yield curve. When the relative growth rate is an increasing function of W as the case is in Fig. 2.4 b for $W < W^*$, the yield curve will bend back under itself and toward the origin.

2.6.2. Two Kinds of Bionomic Equilibria

The shape of the yield curve is in turn of major importance for the equilibrium in the industry and the probability of extinction of the fish stock. The problem of "overcapacity" is recurrent in fisheries; that is, fishing effort exceeds by far the maximum sustainable yield level, catch per unit of effort is "low", and so are even earnings. It will be shown below that "low" catches per unit of effort may be associated with "small" fleets, if the yield curve bends back under itself as in Fig. 2.4 b, and that bionomic equilibria in the backward-bending part of the curve are unstable and greatly increase the probability of extinction. While this is a theoretical result which we do not attempt to support with empirical analysis, it is a fact that there are fisheries which seem to have collapsed from a level of high yields to an extremely unproductive level, where "low" catches per unit of effort are associated with small and not large fleets. Our analysis suggests that this may have to do with a growth relation like the one in Fig. 2.4 b and industrial dynamics of the kind to be discussed below, but this matter needs further empirical analysis, especially the biological aspect.

Figure 2.4 a represents the "classical" case of fisheries economics. Under common property and free access the bionomic equilibrium will always involve excessive effort, as its optimal level is where the distance between the yield curve and the cost line is greatest, but bionomic equilibrium on the other hand is at the point of intersection between the yield curve and the cost line. "Low" cost per unit of effort would be expected to result in a great excess effort and small catches per unit of effort. Fig. 2.4 b suggests that common property and free access may involve inefficiency of a rather different kind. For some cost levels; e.g. as represented by the line C_1 , bionomic equilibrium still implies a greater effort than is needed to obtain maximum stationary rent, but the opposite is true if the cost per unit of effort is low enough. For example, given the cost line C_2 , maximum stationary rent is obtained with the effort f'' , whereas equilibrium effort is f' . The bionomic equilibrium nevertheless is inoptimal, because the total catch is much smaller than it need be with effort at f' . If this bionomic equilibrium has been attained, one may say that the fishery has got stuck in a "low catch trap", resulting from a low and unproductive level of biomass,

where a low mortality and thereby small effort is sufficient to remove all the surplus production that the stock is capable of yielding.

To explain this further, consider the stationary condition

$$(2.3) \quad g(W) = q \cdot f$$

On the left side we have the growth per unit of time, expressed as a fraction of biomass, and on the right side we have the production per unit of time, also expressed as a fraction of biomass (cf. Eq. 2.1' and 2.2). For a constant availability coefficient (q), any expansion of effort clearly implies that a larger *proportion* of the stock will be removed by fishing. This will reduce the stock, but the depletion will be halted if the *relative growth rate* also increases to become equal to the proportion of the stock that is removed by fishing. On the other hand, if effort is expanded and the stock reduced, but the relative growth rate *falls* as a result ($\partial g / \partial W > 0$), as the case is for $W < W^*$ in Fig. 2.4 b, a new equilibrium will be established only if fishing effort is contracted to a lower level than from which it started. Consequently, "low" cost and catch per unit of effort may occur together with a "small" fishing effort when the growth curve is of the kind shown in Fig. 2.4 b.

2.6.3. The Risk of Extinction

The analysis above indicates that equilibria in the backward-bending part of the yield curve may not be so easily obtained; instead of an unproductive fishery caught in a "low catch trap" its basis may have been destroyed altogether by the extinction of the fish population. By the aid of a rudimentary dynamic analysis it is possible to show that the danger of extinction is a good deal greater for populations being characterized by a yield curve as in Fig. 2.4 b than for populations such as in Fig. 2.4 a. Consider a once and for all fall in cost per unit of effort (the same result obtains by analogy for a rise in price). The cost line falls from C_1 to C_2 in Fig. 2.4 a and b, and the bionomic equilibrium effort will be increased in Fig. 2.4 a but decreased in Fig. 2.4 b; yet in both cases the competitive fishery may be expected to respond to the increase in net revenue by expanding effort. The initial response of the fishing industry will thus imply an approach towards equilibrium in Fig. 2.4 a, but a further deviation from equilibrium in Fig. 2.4 b. As effort is expanded the stock will be reduced and the catch per unit of effort thereby depressed, which acts as a brake on the expansion of effort. It is easy to imagine this giving rise to a dynamic path of the fishery such that the new equilibrium will be attained in Fig. 2.4 a, although the industry may "overshoot the target". In Fig. 2.4 b however, it is not sufficient to halt the expansion of effort; it is even necessary to turn it into the reverse, since the adjustment to the new equilibrium requires a contraction and

not an expansion of effort. This would happen when the level of biomass and the catch per unit of effort had fallen far enough. The process might easily be either too slow or start too late; a new equilibrium would then occur only when effort had fallen to the extent that the catch would equal the growth of the new, smaller population.

This comparison between the necessary adjustment processes in the two figures may be helpful for understanding why certain populations have become extinct. The difference between the two populations depicted in Fig. 2.4 a and b is not the *possibility* but the *probability* of extinction as a result of exploitation. Extinction occurs in Fig. 2.4 a if effort exceeds f^* and stays so long enough for the stock to vanish. This could happen with an unfortunate combination of a high rate of entry and a low rate of exit in the industry, but there is no incentive for an immediate expansion of effort beyond f^* unless the cost per unit of effort falls below zero. Extinction also occurs in Fig. 2.4 b if effort is expanded beyond f^* and maintained so long enough, but it will occur too if effort is increased from an equilibrium in that part of the yield curve which bends back toward the origin, provided it is not contracted quickly enough to a still lower level than from which it started. Thus there may be an incentive for an immediate expansion of effort to a level that is incompatible with the continued existence of the population, even at a cost per unit of effort that is positive (in Fig. 2.4 b if cost per unit of effort falls from a level lower than or equal to that which is represented by the line C_1). It seems therefore justified to conclude that a population characterized by a growth curve such as in Fig. 2.4 b faces a greater risk of extinction than the one in Fig. 2.4 a.

One would not normally expect the type of situation described in Fig. 2.4 b to occur in marine fisheries, because of the immense reproductive capacity of fish.¹ Inability of small populations to form schools might be a reason, as the effect of schooling may be to reduce predation, *inter alia* because a predator may become saturated when preying on a large school of fish (cf. Brook and Riffenburgh 1960, Clark 1973 b).

2.6.4. Variable Availability Coefficient and the Backward-Bending Yield Curve

Allowing for the possibility that q is a function of f does not change the conclusion that a growth curve of the kind shown in Fig. 2.4 a ($\partial g/\partial W < 0$ for all W) will not give rise to a yield curve that bends back to the origin.

¹ If the stock-recruitment relation is characterized by "recruitment depensation", it means that $W^* > 0$, and the yield curve bends back toward the origin (Clark 1973 b).

Equation (2.4) then becomes

$$(2.4'') \quad \frac{dW}{df} = \frac{q + (\partial q / \partial f) \cdot f}{\partial g / \partial W} .$$

Now, if the yield curve is to bend back to the origin, it is necessary that the slope of locus ϕ , which is given by Eq. (2.4''), be negative for W in the neighborhood of virgin state equilibrium, approach infinity as W decreases and then change sign as W is reduced below some critical level. This can only happen if $\partial g / \partial W > 0$ and changes sign as W decreases, which is not the case in Fig. 2.4 a. On the other hand the sign of Eq. (2.4'') may very possibly become positive as f increases. It is not unreasonable to suppose that $\partial q / \partial f > 0$ for "low" and $\partial q / \partial f < 0$ for "high" levels of effort. The vessels in a small fleet may aid one another in finding fish for example, while a large fleet may involve congestion. This may give rise to a locus that looks something like ϕ in Fig. 2.5. Congestion rather than a depleted population may thus be the cause of a dome-shaped sustained yield curve, but it ought not to be difficult to distinguish between those two in empirical work.

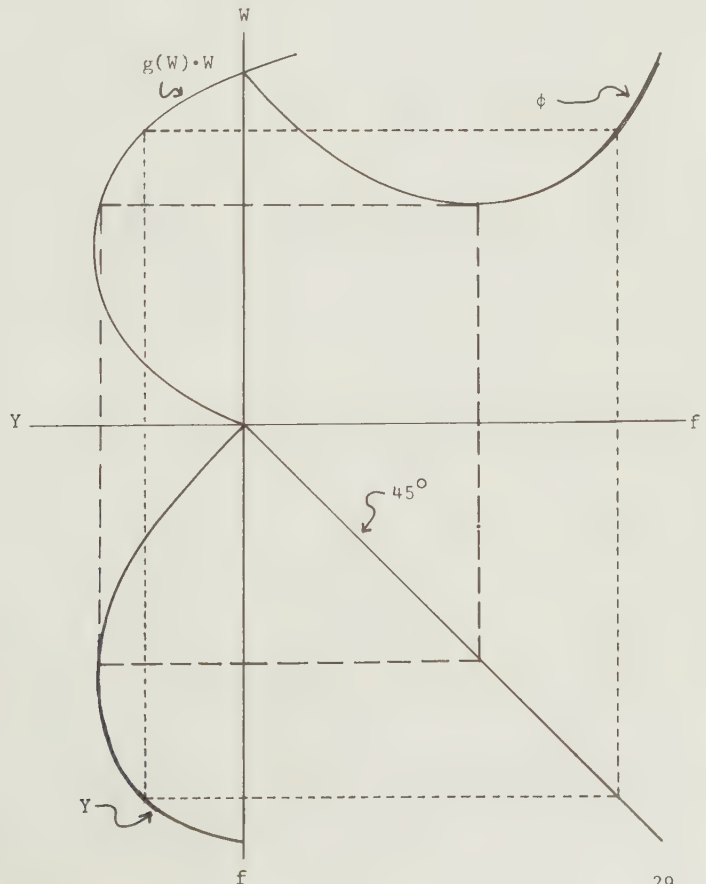


Fig. 2.5

Relaxing, finally, the assumption that q is independent of W we end up with Equation (2.4) again. If its denominator is to approach zero, it is necessary that $\partial q/\partial W < 0$ as long as $\partial g/\partial W < 0$. Defining fishing effort as suits the biologist's purposes; i.e. as units of standard gear used per unit of time, it does not seem likely that the availability coefficient will be a decreasing function of stock, as it would require at least one of the two following conditions to hold: (i) Either the fleet is technologically inefficient in the sense that gear saturation occurs when the stock is dense; i.e. the gear is not removed from the water until after it is saturated and has lost its fishing power, or (ii) the stock becomes more concentrated as it is diminished, so that a unit of gear being placed in a given area will remove a larger proportion of the diminished population. But an adequate definition of effort should, from the economist's point of view, include every activity that gives rise to cost; in addition to laying out the gear everybody will recognize such activities as search, preliminary processing and transportation as being indispensable to any fishery. Let us therefore conceive of fishing effort as being composed of two parts; one that constitutes effective fishing effort in the biologist's sense, and another that includes all "auxiliary" activities such as search, processing at sea and transportation. We wish now to establish whether or not a given level of effort will always remove a constant proportion of the stock to which it is applied, no matter how large or small the fish population is. Supposing that this holds for effective effort in the biologist's sense, the question becomes whether or not the relation between the two components of total effort in the economist's sense will change as a result of diminishing the stock. It is not unreasonable to expect that the search component will increase in relation to effective effort as the stock is diminished, implying that the availability coefficient is an increasing function of stock. Secondly, it is possible that the time needed for preliminary processing at sea will decrease in relation to effective fishing effort as the stock is diminished, because it will then take a longer time to catch a given quantity of fish. This in turn implies an inverse relation between the availability coefficient and stock size. Hence, if this last effect is large enough, it will cause the yield curve to bend back under itself, even though the relative growth rate is a monotonically decreasing function of stock ($\partial g/\partial W < 0$). It is interesting to note the parallel between this and the "predator saturation effect" that may be caused by schooling (cf. above). In this case we would have a "vessel saturation effect", as the time spent processing is relatively long when fishing from a dense stock. On the whole, however, it does not seem very likely that the yield curve will ever be back-

ward-bending if the relative growth rate is a monotonically decreasing function of stock.

2.7. The Impact of Discounting on Optimum Stationary State

In this chapter we have been concerned with stationary states, occasionally referring to the transitory phase from one stationary state to another. By definition any bionomic equilibrium is a stationary state, but we have assumed that the social objective is to find that stationary state which is "best". It was shown that free access to a common property fishery almost certainly would fail to accomplish this.

We shall in Chapter 5 consider whether the choice should be between stationary states at all, but let us now retain the assumption that such is the case. In the past economists have usually been concerned only with the stream of stationary profits when discussing which stationary state would be optimal, but recently Clark (1973 a) has drawn attention to the fact that this is not enough, and that a positive rate of discount will imply a greater optimal stationary fishing effort than that which maximizes the stationary flow of profits. This is where the transitory phase between stationary states becomes important; such transition will temporarily involve a flow of profits which is either larger or smaller than the stationary flow. Discounting of future benefits will imply that these temporary "abnormal" profits must be evaluated against the future stream of stationary profits. To return to the sustainable yield curve, reproduced in Fig. 2.6, economists have been fond of arguing that a point such as C could never be optimal, because the yield Y' could be taken with less cost (point A); hence the optimum level of effort would

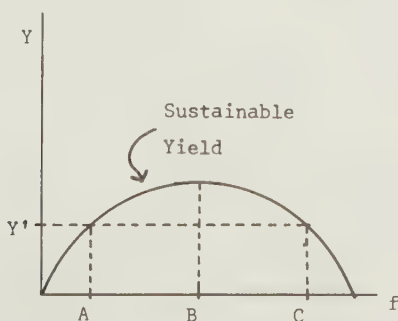


Fig. 2.6

always lie to the left of its maximum sustainable yield level (point B). But this ignores the fact that fishing effort at C involves larger initial catches than A, because the stock will be reduced to a lower equilibrium level. This will be important if the discount rate is high enough. Clark's analysis is of great theoretical significance, since the stationary profit maximization had become something of an established dogma. His analysis of Antarctic whaling (Clark 1973 c) shows that "reasonable" discount rates may imply optimal sustained fishing effort in excess of what is needed for taking the maximum sustainable yield.

Maximization of the present value of rent in the fishery is equivalent to maximizing the integral

$$(2.5) \quad \int_0^{\infty} (fqW - cf)e^{-\rho t} dt$$

where f and W are functions of time, and c is cost per unit of effort. We may set $q = 1$ without any loss of generality, as this affects only the units of measurement used with respect to fishing effort. From Eq. (2.1) and (2.2) we have that, with fishing,

$$(2.6) \quad \dot{W} = G(W) - fW.$$

Maximizing Eq. (2.5) subject to Eq. (2.6) and f bounded between zero and $f_{\max}$ is equivalent to maximizing the Hamiltonian function

$$(2.7) \quad H = f \cdot (W - c)e^{-\rho t} + \mu \cdot (G(W) - fW).$$

As f is the control variable and the Hamiltonian is a linear function of f at any instant, the optimal solution is "bang-bang", with f on either boundary, except when $\partial H / \partial f = 0$ when there is "non-uniqueness of flow" (cf. Shell, 1969). With a "finely tuned" control, the optimal solution approaches a constant f with non-uniqueness of flow at every instant (cf. Neher, 1974). We then have

$$(2.8) \quad (W - c)e^{-\rho t} - \mu \cdot W = 0.$$

The rate of change of the costate variable is

$$(2.9) \quad \dot{\mu} = -\partial H / \partial W = -f e^{-\rho t} + \mu \cdot f - \mu \cdot G'(W)$$

Combining Eq. (2.8) and (2.9) yields

$$(2.10) \quad W \cdot (W - c) = \frac{G(W) \cdot c}{\rho - G'(W)}$$

Since $W > c$ is a necessary condition for any fishing to be profitable, it follows that the left side of Eq. (2.10) is positive. As the numerator of the right side of Eq. (2.10) is nonnegative, the denominator must also be nonnegative. Hence, it follows that, if $\rho > 0$, it is possible that $G'(W) > 0$, in which case fishing effort exceeds the maximum sustainable yield level (cf. Fig. 2.2 a--b). For "low" values of ρ we must have that $G'(W) < 0$. As both

$\rho \rightarrow 0$ and $c \rightarrow 0$ it is clearly necessary that $G'(W) \rightarrow 0$; i.e. maximum sustainable yield is optimal when the opportunity cost of effort is zero and future profits not discounted.

Maximization of stationary rent is equivalent to intertemporal maximization only when the discount rate is zero. Note that, under stationary conditions, $\dot{W} = 0$, and (2.5) may be written, using (2.6)

$$(2.5') \quad \int_0^{\infty} G(W) \cdot (1 - c/W) \cdot e^{-\rho t} dt$$

Differentiating the integrand with respect to W and setting the result equal to zero gives

$$(2.11) \quad W \cdot (W - c) = \frac{G(W)c}{-G'(W)}$$

which is equal to (2.10) for $\rho = 0$. If on the other hand $\rho \rightarrow \infty$, it is necessary that $(W - c) \rightarrow 0$. Hence, bionomic equilibrium under common property where the sustained rent is nil is in fact optimal when the discount rate approaches infinity.

The impact of discounting on the optimal stationary effort lends itself readily to a common sense interpretation. Consider a lightly exploited stock of fish where the adjustment to optimum involves an expansion of effort, no matter what the rate of discount. A rapid reduction of the stock involves benefits in the form of large near term catches, which have to be balanced against the fact that a lower level of stock implies a higher cost per unit of fish caught in the long term. Clearly, if near term benefits are valued very much higher than long term ones, it is natural that the stock should be reduced to a low level which in the long term implies a sustained catch taken by the higher of the two levels of effort with which it is compatible. In terms of Fig. 2.6, it is certainly true that taking the sustained yield Y' with effort C rather than A means less economic rent than need be once stationary conditions have been attained, but the large initial reduction of stock involves near term benefits that will outweigh the long term losses from the cost differential between A and C , if the rate of discount is sufficiently high.

Conversely, consider a resource that is being exploited at bionomic equilibrium rate. Provided the discount rate is less than infinity, intertemporal maximization of rent will involve waiting while the stock replenishes itself to the optimum stationary level. The higher is the rate of discount the less is the willingness to wait for the fishery to be resumed and the lower will be the optimum level of stock, possibly lower than that which sustains maximum stationary yield, which implies effort in excess of B .

An assertion frequently encountered, especially in biological litera-

ture, is that any reduction of stock below maximum sustainable yield level constitutes overfishing and should be avoided. The present analysis shows that this is not quite true, despite its strong common sense appeal. Such overfishing may indeed be desirable from the economic point of view, given a sufficiently high discount rate. This is no apology for the competitive fishery and its inherent tendency to overfishing, since (i) intertemporal maximization of net benefits presupposes a single authority, acting either in the private or public interest, and (ii) for a situation like the one prevailing in bionomic equilibrium under common property to be optimal, it is necessary that the rate of discount be infinitely high. The ultimate conclusion is that time preference is one among several variables that reflect the economic environment and must be taken explicitly into account by any managing authority.

3.1. Introduction

Economics of fisheries has hitherto been concerned almost exclusively with the exploitation of one species in isolation, without explicitly considering relations between species. This may appear surprising, as the fundamental fact of life in the ocean as well as on land is the transfer of organic material through a food chain, or more adequately, a food web, one species feeding on others. Yet it is understandable why food web relations have been ignored. First, the present state of fisheries science hardly permits a quantification of food web relations, without which the analysis of their impact on optimal exploitation is only qualitative. Second, fishing has traditionally been aimed at relatively very few species at the top of the food chain, in which case it may be permissible to ignore ecological interdependence and assume a constant supply of food for the exploited species, since the biomass further down in the chain may be expected to increase rather than decrease as a result of fishing. Alternatively, the food supply may be regarded as a function of the exploited stock and subsumed in a general growth function of a "Schaeferian" type (cf. Chapter 2). The main reason why an economist would be interested in ecological interdependence under those circumstances would be possible competition for food between exploited species.

The single-species approach is presently becoming less and less adequate. In the last couple of decades world fisheries have turned to exploiting "new" species, previously left largely or wholly unfished. A substantial part of the increase in total catches during this period is due to these "new" fisheries, examples of which are the anchoveta fishery off the Pacific coast of South America and the North Atlantic capelin fishery. Fishery biologists consider that a further increase in total world catch is possible--perhaps by more than 100%--but recognize that it would similarly require the extension of fishing to still unexploited, or lightly exploited, species. The great uncertainty regarding the maximum sustainable world catch is in turn the result of insufficient knowledge regarding the fraction of biomass transferred between links in the food chain and how that fraction might be affected by fishing.¹

In order to maximize total catch it would be desirable, *ceteris paribus*, to exploit species at as low level in the food chain as possible, because of

¹ Cf. Dickie (1972).

the loss of energy involved in transferring organic material from one species to another. This suggests that management of fisheries be concerned with optimizing a system of interrelated species rather than with bits and pieces thereof, like unit stocks. But even though the total quantity of fish caught in the world may be an interesting figure, it is not of any great relevance to consider the maximization of an aggregate like that. Consumers evaluate a given quantity of fish differently according to which species it comes from because of qualitative differences, and not only by "nutritional value", e.g. protein content. Even if an overriding priority were to be given to "nutrition", it would still not necessarily be optimal to maximize yield in quantitative terms only; e.g. protein yield, as the amount of resources required to harvest a given quantity of protein varies from one stock, or species, to another.

Given prices and costs, or demand and cost functions, which reflect the social utility of fish caught and utility forsaken by fishing, what will be the optimal exploitation of a system of interrelated species and how would competitive fishermen be expected to react to market prices? In Chapter 2 we discussed this question in the context of single-species fisheries, concluding that profit-maximizing competitive fishermen would fail to take into account that a fish left in the sea has some value, or shadow price, as an input into future production of fish. That conclusion remains valid even in a multi-species fishery, but the value of a fish left in the sea will then depend not only upon its capacity to grow and reproduce itself, but also on its effect on other exploited species.

Stock externalities of this kind may in theory be corrected by imposing a Pigovian tax on catch, or fishing effort, which serves to decrease the value of the marginal fish caught by its value as an input into future production of fish. Such taxes have been considered by Smith (1968, 1969) and by Burt and Cummings (1970) for the single-species case. The dynamic pattern of such taxes may be quite complicated (cf. Burt and Cummings 1970), but as long as the analysis is restricted to stationary states the optimal tax is always positive and increases as the price of fish increases in relation to the cost of fishing effort. This is not surprising, as the purpose of the tax is to confiscate the economic rent, or that part of it which provides incentives to excessive fishing effort.

Quirk and Smith (1970) have extended the analysis of Pigovian taxes to the multi-species case, but their model is general to the point of being inconclusive. We shall take a less general approach and consider stationary states only. This in our opinion demonstrates more clearly some fundamental

differences between the single- and multi-species case. We shall ignore the impact of discounting on optimal stationary states and the occurrence of other externalities than stock externalities, e.g. congestion or gear selectivity (cf. Smith 1969).

We shall begin by considering Pigovian taxes in a single-species model of a common-property fishery. In Section 3.3 the analysis is extended to a multi-species model where it is shown that it may under some circumstances be optimal to subsidize the exploitation of certain species. In Section 3.4 we take a closer look at externalities arising from predator-prey relations in a Lotka-Volterra model. The result is different from the single-species case in some important respects; not only should the exploitation of predators in some cases be subsidized, but an unexpected case of market failure may occur, as the optimal fishing effort allocated to a particular species of fish in some cases increases (decreases) when the relative price of that species falls (rises).

3.2. Pigovian Taxes in Single-Species Fisheries

3.2.1. The Model

Regarding the fishing industry in isolation, the social utility function may be defined as

$$(3.1) \quad U = U(Y, f),$$

where U is social utility, which we shall regard as being cardinal and measured in some numéraire commodity. Furthermore, we shall make the conventional assumption that the marginal utility of fish caught is either constant or a decreasing function of fish, and the marginal disutility of fishing effort is either constant or an increasing function of fishing effort.

From Chapter 2 we have the stationary condition

$$(3.2) \quad Y = G(W).$$

The production function of the fishery will be defined as

$$(3.3) \quad Y = H(f, W).$$

From a social point of view, the management problem may be regarded as the maximization of Eq. (3.1), subject to Eq. (3.2) and (3.3). The Lagrangian expression of this problem is

$$(3.4) \quad L(Y, f, W, \mu, \gamma) = U(Y, f) - \mu \cdot \{Y - G(W)\} - \gamma \cdot \{Y - H(f, W)\}.$$

The manager attempts to find the combination of biomass and fishing effort which maximizes Eq. (3.4). The necessary conditions for an interior maximum are

$$(3.5) \quad \partial U / \partial Y = \mu + \gamma$$

$$(3.6) \quad -\partial U / \partial f = \gamma \cdot (\partial H / \partial f)$$

$$(3.7) \quad \mu = - \gamma \cdot \frac{\partial H / \partial W}{\partial G / \partial W} .$$

If the partial derivative of the production function with respect to fishing effort ($\partial H / \partial f$) is interpreted as the increase in a competitive fisherman's catch resulting from his increase of fishing effort--or entry to the fishery--it follows that the multiplier μ can be interpreted as the optimal Pigovian tax on catch. To consider this further, let us recall the production function as defined in Chapter 2:

$$(3.8) \quad H(f, W) = f q W .$$

If the availability coefficient (q) is regarded as being independent of fishing effort,¹ we have that the catch per unit of effort is equal to the partial derivative of the production function with respect to f :

$$(3.9) \quad \partial H / \partial f = q W = Y / f .$$

We have previously identified the catch per unit of effort as being equal to the catch that a competitive fisherman may be expected to reckon as his "marginal product". This does not, strictly speaking, require that all fishermen are alike, although it is convenient to explain it by referring to homogeneous fishermen as we did in Chapter 2. For fishermen with varying skills--and/or fishing fleets of qualitatively different vessels--fishing effort may be regarded as being measured in homogeneous units, but with skill differences implying that more and more is being forsaken for each unit added. Equilibrium in the industry then requires that

$$(3.10) \quad p^S \cdot (Y / f) = c ,$$

where p^S is the price of fish encountered by the seller and c is the opportunity cost of a marginal unit of effort. Interpreting $\partial U / \partial Y$ as the buyer's price of fish (p^b) and $-\partial U / \partial f$ as the opportunity cost of a marginal unit of effort, it follows from Eq. (3.5), (3.6), (3.9) and (3.10) that in optimum

$$(3.11) \quad p^b = \mu + p^S .$$

Hence, the multiplier γ is equal to the price that fishermen should encounter on the market, while the multiplier μ may be interpreted as the Pigovian tax on catch at the optimum, implying no incentives to deviate from optimum once it had been attained.

This simple model captures the essentials of Pigovian taxes to correct for stock externalities. In this case the externality is caused only by competitive fishermen's failure to take account of the relation between fishing effort, equilibrium stock and growth. Consequently, the Lagrangean multiplier which corresponds to the growth constraint also is the optimal tax. This would not be quite true if the availability coefficient (q) varies with fish-

1 Cf. Chapter 2 for a discussion of this assumption.

ing effort; the tax would then have to include a correction for that as well. We shall, however, not consider that case further, as it adds little of interest in principle.

3.2.2. A Tax on Catch or a Tax on Effort?

To return to the stationary yield curve derived in Chapter 2 (Fig. 3.1),

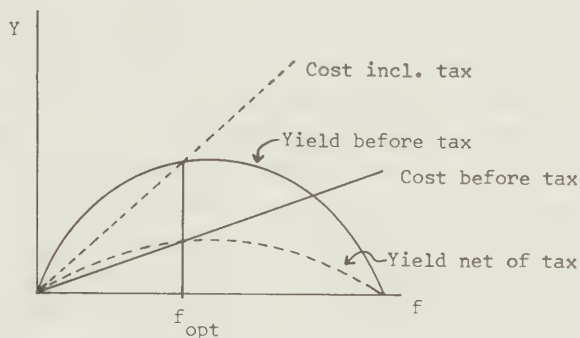


Fig. 3.1

the effect of the tax is to displace the yield curve--in monetary terms--downwards, in order that optimum effort coincide with the equilibrium effort in the fishery. With no skill differences between fishermen this amounts to confiscating all economic rents in the fishery, as nothing less suffices to remove the incentives to entry to the industry. Taking account of skill differences would modify this to having the marginal fisherman just covering his opportunity cost, with some skill rents being collected by intramarginal fishermen (cf. Turvey 1964).

The same result could, in theory, be obtained by taxing fishing effort. In terms of Fig. 3.1 this amounts to rotating the cost curve upwards until optimal and equilibrium effort coincide. By Eq. (3.5) and (3.7), Eq. (3.6) implies

$$(3.12) \quad - (\partial U / \partial f) \cdot \left(1 - \frac{\partial H / \partial W}{\partial G / \partial W} \right) = \frac{\partial U}{\partial Y} \cdot \frac{\partial H}{\partial f}.$$

Interpreting the partial derivatives of the utility function in the same way as before, the second term within brackets may be interpreted as the optimal tax on fishing effort, expressed as a fraction of the cost of a marginal unit of effort. The two methods need not in practice be quite equivalent however. Fishing effort has been treated here as one single factor of production, but in reality it is a composite factor of several inputs, all of which would, ideally, have to be taxed in an optimal way. A tax on catch is therefore like-

ly to be more simple, as far as "simple" is an adequate expression in this context. It may prove quite complicated in practice to use Pigovian taxes, for economic and technical reasons only, to say nothing of political constraints. Note that a given optimal tax on catch (Eq. 3.7) or fishing effort (Eq. 3.12) requires not only a particular set of prices, but also particular growth and production functions. As these functions are defined with respect to unit stocks, there is no reason to expect the optimal taxes to be equal for all stocks, even though the price of fish and effort were the same with respect to all. This means that the tax on catch or fishing effort would have to be varied according to the unit stock exploited, in case a given fishing fleet could be directed to any one of different unit stocks at any given time. The most productive stocks would, *ceteris paribus*, have to be taxed more heavily than the less productive ones, as the superior fishing grounds tend to be more excessively exploited (cf. Chapter 2).

Despite considerable theoretical work by economists on Pigovian taxes in fisheries, this method of regulation has hardly been practised anywhere. The recent licence limitation scheme for the salmon fisheries in British Columbia is to our knowledge the closest that fisheries' management authorities have come to put such ideas into practice. On the other hand there are a number of examples of management schemes that have attempted to control the exploitation in physical terms only, without taxing economic rent. In such cases economic rent tends to become dissipated, not through overexploitation in the sense that the stock is reduced below maximum sustainable yield level, but through excessive capacity that manifests itself in short seasons, speedy boats, etc.¹

3.2.3. The Interpretation of μ and γ

In order to interpret μ and γ , let us differentiate the utility function around the optimum, denoting its partial derivatives with respect to Y and f by p and $-c$ and use the stationary condition (3.2):

$$(3.13) \quad dU = p \cdot (\partial G / \partial W) \cdot dW - c \cdot df.$$

As the production constraint (2.3) must also be satisfied we have

$$(3.14) \quad (\partial G / \partial W) \cdot dW = (\partial H / \partial W) \cdot dW + (\partial H / \partial f) \cdot df,$$

which we may write

$$(3.14') \quad df = \frac{dW \cdot (\partial G / \partial W - \partial H / \partial W)}{\partial H / \partial f}.$$

Eq. (3.13) may now be written, using Eq. (3.5) and (3.6):

$$(3.13') \quad dU = \left[\mu \cdot (\partial G / \partial W) + \gamma \cdot (\partial H / \partial W) \right] \cdot dW.$$

¹ Cf. Crutchfield and Zellner (1963) on the Pacific halibut fishery, and Crutchfield and Pontecorvo (1969) on Pacific salmon.

For variations around the optimum, Eq. (3.13') necessarily equals zero. The term $\partial G/\partial W$ represents the sacrifice of stationary yield required for a marginal increase in equilibrium stock size. The term $\partial H/\partial W$ shows the increase in output which would result from a marginal increase in stock size, *with fishing effort remaining constant*. Fishing effort does not remain constant however; it must be diminished in order to increase stock size. The stationary yield decreases as a result, because it is never optimal to exploit the stock beyond maximum sustainable yield level in absence of discounting. The term $\partial H/\partial W$ therefore represents a marginal relaxation of the production constraint. Now, if the sacrifice of stationary yield is valued at the price μ , whereas the resulting relaxation of the production constraint is valued at γ , the sum of the two is zero at the optimum, saying that the value of a fish left to grow and replenish itself is equal to the value of the relaxation of the production constraint. The multiplier γ may therefore be interpreted as the net social value of a unit of biomass caught and the multiplier μ as the value of a unit of biomass left unexploited.

By Eq. (3.7) the optimal tax on catch (μ) depends on the value of the partial derivatives of the growth function and the production function at the optimum. In the absence of discounting, $\partial G/\partial W$ is always negative at the optimum, from which follows that the optimal tax is always positive. From Eq. (3.7) it may also be seen that the optimal tax approaches infinity as the optimal rate of exploitation approaches maximum sustainable yield level. From Eq. (3.6) it follows that the net social value of a fish caught (γ) approaches zero as the opportunity cost of effort approaches zero, which is not surprising, as one would expect that the stock should be exploited to the point where the marginal catch contributes nothing to the welfare of society when exploitation is costless. This is precisely what happens when the price of fish is wholly absorbed by the tax; i.e. when the price of fish is equal to its value as an input into future production of fish.

3.3 Pigovian Taxes in Multi-Species Fisheries

Broadening the view to take account of interrelations between species opens up a Pandora's box of externalities. It is possible to identify at least three types of inter-species relations that give rise to externalities: First, *ecological externalities*; i.e. food web relations through predation or competition. Secondly, *incidental catches*; i.e. although fishing effort is aimed at certain species, others are unavoidably caught as well. Thirdly, *catch interference*; i.e. one species of fish adversely affects the catch of another, e.g. by destroying the fishing gear or getting trapped instead of the desired species.

The difference between externalities of the second and third type above may be conceptual rather than real; what if an undesired species gets trapped in the gear and is thrown away as trashfish? Then, what is regarded as trashfish by one fleet may be desired by another, owing to artificial barriers to trade, physical impossibility or commercial unprofitability to serve different markets at the same time. We shall not consider the problem of incidental catches further here, but it may be noted that the species yielding the highest profit will also be most important for influencing the allocation of fishing effort. The overall efficiency of the fishing fleet may be improved by creating a market for incidental catches, provided that these are desired by some consumers. On the other hand we shall devote some attention to the other two types of externalities. (On "incidental catches", cf. e.g. Clark 1973 d).

3.3.1. A General Model of Interdependent Species

In a multi-species model both Y and f are vectors. Excluding incidental catches amounts to assuming that each species of fish can be fished with a perfectly selective process. The social utility function is therefore

$$(3.1') \quad U = U(Y_1, \dots, Y_n; f_1, \dots, f_n),$$

where n is the number of species considered. The stationary condition becomes

$$(3.2') \quad Y_i = G_i(W_1, \dots, W_n) \quad i=1, \dots, n$$

and the production function becomes

$$(3.3') \quad Y_i = H_i(f_i; W_1, \dots, W_n) \quad i=1, \dots, n$$

The Lagrangean function of the manager's maximization problem is

$$(3.4') \quad L(Y, f, W, \mu, \gamma) = U(Y, f) - \mu \cdot (Y - G(W)) - \gamma \cdot (Y - H(W, f)),$$

where U is a scalar, but μ , γ , Y , f , G and H are vectors of n elements. The necessary conditions for an interior maximum are

$$(3.5') \quad \partial U / \partial Y = \mu + \gamma$$

$$(3.6') \quad - \partial U / \partial f = \gamma \cdot (\partial H / \partial f)$$

$$(3.7') \quad \mu = - \gamma \cdot (\partial H / \partial W) \cdot (\partial G / \partial W)^{-1}.$$

The assumption of a perfectly selective fishery with regard to species implies that $\partial H / \partial f$ is a diagonal matrix, while the off-diagonal elements in the matrices $\partial H / \partial W$ and $\partial G / \partial W$ reflect interdependence between species. Therefore, Eq. (3.9) is still relevant

$$(3.9') \quad \partial H_i / \partial f_i = q_i W_i = Y_i / f_i, \quad i=1, \dots, n$$

where i denotes the i 'th species. Equilibrium in the industry requires that no overnormal profits be possible with regard to any species:

$$(3.10') \quad p_i^s \cdot (Y_i / f_i) = c_i \quad i=1, \dots, n$$

Equations (3.5'), (3.6'), (3.9') and (3.10') imply as before:

$$(3.11') \quad p_i^b = \mu_i + p_i^s, \quad i=1, \dots, n$$

i.e. that the multiplier μ_i may be interpreted as the optimum tax on catch of species i and that the multiplier γ_i is equal to the price of species i which producers should encounter on the market.

Let us now consider the effect of interdependence between species on the optimal tax. It is convenient to deal with each type of externality at a time, so let it first be assumed that there is no ecological interdependence but only interference of one species with the catch of another. In that case the matrix $\partial G / \partial W$ is diagonal. Suppose now that species j interferes with the catch of species i , which implies $\partial H_i / \partial W_j < 0$. The optimal tax on species j is (cf. Eq. 3.7').

$$(3.7'') \quad \mu_j = -\gamma_i \cdot \frac{\partial H_i / \partial W_j}{\partial G_j / \partial W_j} - \gamma_j \cdot \frac{\partial H_j / \partial W_j}{\partial G_j / \partial W_j}.$$

If species j is not fished beyond maximum sustained yield level we have that $\partial G_j / \partial W_j < 0$ and the interpretation of (3.7') is straightforward.¹ The optimal tax, μ_j , is seen to decrease the more detrimental the stock of species j is for the exploitation of species i (i.e. the greater $|\partial H_i / \partial W_j|$ is). A high net social value of a unit caught of species i vis-à-vis species j ($\gamma_i \gg \gamma_j$) has the same effect. Thus it is possible that the exploitation of a species which is of little direct value to consumers but a grave nuisance for the catch of a species that fetches a high price on the market should be subsidized; a fish of a species like that being left to grow and replenish itself is then of no value. A case in which subsidization of fishing has been proposed for precisely these reasons is the exploitation of dogfish off the coast of British Columbia, which interferes with the fishery for high priced salmon.

It is more difficult to give an interpretation of Eq. (3.7') in the case of ecological interdependence between species, partly because the sign of $\det (\partial G / \partial W)$ is ambiguous. We shall therefore take a different approach and solve a numerical Lotka-Volterra model in order to bring forward some interesting implications of ecological interdependence. We shall present this analysis in Section 3.4, but let us consider, first, the interpretation of μ and γ in a two-species model.

3.3.2. The Interpretation of μ and γ

It is possible to interpret the multipliers μ and γ as the value of a unit of fish left unexploited and net social value of a unit of fish caught,

1 Possibly it is optimal to exploit species j beyond maximum sustained yield level, owing to the detrimental effect on species i , in which case Eq. (3.7') becomes much less transparent.

exactly as in the single-species model presented in section 3.2. Let us consider, first, species interdependence via the production function, where species j again interferes with the catch of species i . Consider a variation around the optimum such that the stock of species j is increased in order to save fishing effort. The increase in abundance of species j will however make it necessary to devote greater effort to maintaining the yield of species i . Using the growth restriction (3.2') and setting the partial derivatives of U equal to p and $-c$ respectively, the change in the social utility is

$$(3.15) \quad dU = p_j \cdot (\partial G_j / \partial W_j) \cdot dW_j - c_j \cdot df_j - c_i \cdot df_i.$$

Assuming that the catch of species j is unaffected by the abundance of any other species, the change in effort is given by Eq. (3.14') in Section 3.2:

$$(3.14') \quad df_j = \frac{dW_j \cdot (\partial G_j / \partial W_j - \partial H_j / \partial W_j)}{\partial H_j / \partial f_j}.$$

Differentiating the production function for species i gives

$$(3.16) \quad dY_i = (\partial H_i / \partial f_i) \cdot df_i + (\partial H_i / \partial W_i) \cdot dW_i + (\partial H_i / \partial W_j) \cdot dW_j.$$

The change in fishing effort for species i that is necessary to maintain the same yield as before is given by setting Eq. (3.16) equal to zero. As $\partial G / \partial W$ is by assumption a diagonal matrix in this case and the growth rate of species i does not change, it follows that $dW_i = 0$. Hence,

$$(3.17) \quad df_i = - \frac{(\partial H_i / \partial W_j) \cdot dW_j}{\partial H_i / \partial f_i}$$

Using Eq. (3.5'), (3.6'), (3.14') and (3.17), Eq. (3.15) may be written

$$(3.15') \quad dU = (\mu_j \cdot (\partial G_j / \partial W_j) + \gamma_j \cdot (\partial H_j / \partial W_j) + \gamma_i \cdot (\partial H_i / \partial W_j)) \cdot dW_j.$$

The first two terms within brackets have the same interpretation as before, and the last one shows the net social value of strengthening the production constraint for species i by increasing the stock of species j . The two last terms within brackets therefore show the value of the impact on the production constraint resulting from sacrificing a unit of stationary yield of species j , whereas the first term shows the sacrifice of stationary yield, valued at the price μ_j . As Equation (3.15') is equal to zero at the optimum, it is possible to interpret μ_j as the value of a unit of fish of species j left unexploited, and γ_j (γ_i) as the net social value of a unit caught of fish of species j (i), exactly as in the single-species case.

Turning now to the case of ecological interdependence, suppose that species i and j are directly related in the food web and consider a variation in the stationary yield of species j only, maintaining the yield and growth rate

of species i constant. This requires that fishing effort be altered with respect to both species. Variation of the utility function, using the stationary condition (3.2'), gives

$$(3.18) \quad dU = p_j \cdot \left((\partial G_j / \partial W_j) \cdot dW_j + (\partial G_j / \partial W_i) \cdot dW_i \right) - c_j \cdot df_j - c_i \cdot df_i$$

Differentiating the production function for species j and equating the result to the change in the rate of growth implied by a change in the stock of both species gives

$$(3.19) \quad (\partial G_j / \partial W_j) \cdot dW_j + (\partial G_j / \partial W_i) \cdot dW_i = (\partial H_j / \partial W_j) \cdot dW_j + (\partial H_j / \partial f_j) \cdot df_j,$$

which may be solved for df_j :

$$(3.19') \quad df_j = \frac{(\partial G_j / \partial W_j) \cdot dW_j + (\partial G_j / \partial W_i) \cdot dW_i - (\partial H_j / \partial W_j) \cdot dW_j}{\partial H_j / \partial f_j}.$$

As the yield of species i is supposed to be maintained, the change of effort for species i is given by setting Eq. (3.16) equal to zero as before. With $\partial H_i / \partial W_j = 0$ this gives

$$(3.20) \quad df_i = - \frac{(\partial H_i / \partial W_i) \cdot dW_i}{\partial H_i / \partial f_i}.$$

Equation (3.18) may now be written, using (3.5'), (3.6'), (3.19') and (3.20):

$$(3.18') \quad dU = \mu_j \cdot \left((\partial G_j / \partial W_j) \cdot dW_j + (\partial G_j / \partial W_i) \cdot dW_i \right) + \gamma_j (\partial H_j / \partial W_j) \cdot dW_j + \gamma_i (\partial H_i / \partial W_i) \cdot dW_i.$$

The terms within brackets show the decrease in stationary yield which is required to increase the biomass of species j ; the latter term takes care of the induced change in the biomass of species i , which in turn affects the growth rate of species j . The last two terms on the right show the net social value of relaxing the production constraint for both species by a marginal sacrifice in stationary yield of species j . As Eq. (3.18') equals zero, the multiplier μ_j may again be interpreted as the value of a unit of fish of species j left unexploited as an input into the biological system, while γ_j and γ_i are the net social values of a unit of fish caught of the two species.

3.4. A Lotka-Volterra Model of Ecological Interdependence

The model which we shall use for further study of the implications of ecological interdependence is based on a variant of the Lotka-Volterra growth equations, used earlier by Larkin (1966) for a different purpose. It is to be regarded as a convenient substitute for qualitative calculus, and the results obtained are on the same level of accuracy; that is, showing the direction of change in certain variables for a given direction of change of some parameter.

The numerical solutions do not carry any specific meaning, as the values assigned to the biological and technological parameters are not based on any empirical studies.

The model incorporates two species in a predator-prey relation to each other. If species 1 is the prey and species 2 the predator, the growth rates of the two species are, in absence of fishing

$$(3.21) \quad \dot{W}_1 = a_1 W_1 - b_1 W_1^2 - e_1 W_1 W_2 \quad a_1, b_1, e_1 > 0$$

$$(3.22) \quad \dot{W}_2 = a_2 W_2 - b_2 W_2^2 + e_2 W_2 W_1$$

where the coefficients e_i reflect the degree of ecological interdependence between the species. Since we shall restrict ourselves to stationary conditions, the time derivatives in Eq. (3.21) and (3.22) may be replaced by the production per unit of time, Y_i . So interpreted, Eq. (3.21) and (3.22) correspond to constraint (3.2') in the social optimization problem above. As in Chapter 2, we shall assume a constant availability coefficient, so the production function of the fishery for species i is

$$(3.23) \quad Y_i = f_i q_i W_i, \quad q_i > 0,$$

which corresponds to constraint (3.3') in the social optimization problem.

The matrix $(\partial G / \partial W)^{-1}$ becomes

$$(3.24) \quad \frac{1}{\Delta} \begin{bmatrix} a_2 - 2b_2 W_2 + e_2 W_1 & e_1 W_1 \\ -e_2 W_2 & a_1 - 2b_1 W_1 - e_1 W_2 \end{bmatrix}$$

where Δ is the determinant of matrix $\partial G / \partial W$,

$$(3.25) \quad \Delta = (a_1 - 2b_1 W_1 - e_1 W_2)(a_2 - 2b_2 W_2 + e_2 W_1) + e_1 W_1 e_2 W_2.$$

We then obtain the following expressions for μ_i , the optimal tax:

$$(3.26) \quad \mu_1 = -(1/\Delta) \cdot (\gamma_1 q_1 f_1 \cdot (a_2 - 2b_2 W_2 + e_2 W_1) + \gamma_2 q_2 f_2 \cdot (-e_2 W_2))$$

$$(3.27) \quad \mu_2 = -(1/\Delta) \cdot (\gamma_1 q_1 f_1 \cdot (e_1 W_1) + \gamma_2 q_2 f_2 \cdot (a_1 - 2b_1 W_1 - e_1 W_2)).$$

Apparently, it is not possible to give an analytical interpretation of the different elements which μ consists of, except the not very revealing statement that this particular relation holds at the optimum. The determinant, Δ , has an indeterminate sign, because $\partial G_2 / \partial W_2$ has, now that we are dealing with a system of interacting species. The approach taken will therefore be to optimize the social utility function and calculate the optimal values of taxes, fishing effort and catches for various configurations of prices. For simplicity we shall assume a linear utility function, where p_i denotes the increase in social utility resulting from catching a unit of fish of species i , while c is the loss of utility per unit of fishing effort:

$$(3.28) \quad \max \sum_{i=1}^2 p_i q_i f_i w_i - c f_i.$$

Taking restrictions (3.2') and (3.3') into account simultaneously; that is, setting Eq. (3.23) equal to Eq. (3.21) and (3.22) respectively, makes it possible to solve for stock in terms of fishing effort:

$$(3.29) \quad w_1 = \frac{(a_1 - q_1 f_1) b_2 - e_1 (a_2 - q_2 f_2)}{b_1 b_2 + e_1 e_2}$$

$$(3.30) \quad w_2 = \frac{(a_2 - q_2 f_2) b_1 + e_2 (a_1 - q_1 f_1)}{b_1 b_2 + e_1 e_2}.$$

The partial derivatives of the objective function are

$$(3.31) \quad p_i q_i \cdot (w_i + f_i \cdot (\partial w_i / \partial f_i)) + p_j q_j f_j \cdot (\partial w_j / \partial f_i) - c, \quad i, j=1,2; i \neq j,$$

where $\partial w_i / \partial f_i$ and $\partial w_j / \partial f_i$ can be calculated from Eq. (3.29) and (3.30). With fishing effort as a numéraire ($c=1$) the model was optimized for different configurations of prices, using the gradient method to find the optimum. Table 3.1 and Fig. 3.2 summarize the results for one set of values assigned to the interdependence coefficients (e_1 and e_2), Table 3.2 and Fig. 3.3 for another. Both sets of results are qualitatively similar. Note that in the left (right) part of both figures the price of species 2 (species 1) is fixed and equal to one while the price of species 1 (species 2) varies.

The results with respect to the prey (species 1) are most similar to the single-species case. When the price of this species varies with the price of the predator held constant (left half of Fig. 3.2 and 3.3 and lower half of Tables 3.1 and 3.2), fishing effort for the prey species is an increasing function of its price, approaching maximum sustainable yield level asymptotically. The tax to be levied on the catch of the prey species is also an increasing function of its price, exactly as in the single-species model. Ecological interdependence does, however, affect the optimal rate of exploitation of the prey and the optimal tax on prey catch, as is best demonstrated by the right half of Fig. 3.2 and 3.3 (upper half of Tables 3.1 and 3.2). In that case both the price of the prey and the cost of fishing effort are held constant, and if the exploitation of this fish did not affect any other fisheries, the optimal rate would not change as long as there is no constraint on total capacity to be considered. In effect the optimal rate of exploitation of the prey is a decreasing function of the price of the predator, because a prey fish which is left unexploited becomes increasingly valuable in its capacity of an input into the ecological system as the price of the predator increases.

On the other hand, the results with respect to the predator species are for some price configurations entirely different from the single-species case.

TABLE 3.1

 $a_1=1, a_2=0.5, b_1=1.25 \cdot 10^{-4}, b_2=4 \cdot 10^{-4}, e_1=10^{-4}, e_2=5 \cdot 10^{-5}, q=10^{-3}, q_2=2 \cdot 10^{-3}$

<u>P₁=1</u>									Sign	Rent (U)
P	W ₁	W ₂	f ₁	f ₂	Y ₁	Y ₂	u ₁	u ₂	Δ	
4.0	4746.8	867.1	319.9	195.2	1518.7	338.6	0.789	3.423	+	2357.9
3.8	4710.7	863.2	324.8	195.1	1530.2	336.9	0.788	3.221	+	2290.4
3.6	4674.9	859.0	329.7	195.1	1541.5	335.1	0.786	3.018	+	2223.2
3.4	4639.3	854.7	334.6	195.0	1552.4	333.4	0.784	2.815	+	2156.3
3.2	4604.0	850.1	339.5	195.1	1563.0	331.7	0.783	2.612	+	2089.8
3.0	4569.0	845.2	344.4	195.2	1573.4	329.9	0.781	2.408	+	2023.6
2.8	4534.4	839.9	349.2	195.4	1583.5	328.2	0.779	2.205	+	1957.8
2.6	4500.1	834.1	354.1	195.7	1593.4	326.4	0.778	2.001	+	1892.4
2.4	4466.2	827.8	358.9	196.1	1603.1	324.7	0.776	1.796	+	1827.3
2.0	4400.0	812.5	368.7	197.5	1622.5	320.9	0.773	1.385	+	1698.1
1.8	4367.9	803.0	373.7	198.6	1632.3	318.9	0.771	1.177	+	1634.1
1.6	4336.6	791.6	378.8	200.1	1642.5	316.8	0.769	0.968	+	1570.6
1.4	4306.7	777.5	383.9	202.2	1653.4	314.4	0.768	0.757	+	1507.4
1.0	4253.2	734.2	394.9	209.5	1679.7	307.6	0.765	0.319	-	1382.9
0.6	4222.4	634.2	408.8	228.7	1726.0	290.1	0.763	-0.188	-	1262.6
0.4	4239.2	502.7	419.8	255.4	1779.7	256.8	0.764	-0.595	-	1207.2
0.2	4388.6	31.0	448.3	353.5	1967.5	21.9	0.772	-15.917	-	1170.1

	<u>P₂=1</u>									
1.7	4127.8	380.8	445.9	277.0	1840.8	211.0	1.458	-.313	-	2617.3
1.5	4137.9	482.8	434.5	256.9	1797.9	248.0	1.258	-.036	-	2253.4
1.2	4185.4	633.8	413.4	227.9	1730.4	288.9	0.961	0.211	-	1724.1
1.0	4253.2	734.2	394.9	209.5	1679.7	307.6	0.765	0.319	-	1382.9
0.8	4374.6	836.0	369.6	192.2	1616.8	321.3	0.571	0.402	+	1053.0
0.6	4603.8	942.5	330.3	176.6	1520.5	332.9	0.383	0.469	+	738.3
0.4	5097.2	1072.5	255.6	162.9	1302.9	349.4	0.204	0.534	+	452.1
0.3	5637.9	1141.6	181.1	162.6	1021.0	371.3	0.123	0.562	+	333.9
0.25	6075.2	1190.0	121.6	163.9	738.8	390.0	0.085	0.580	+	289.2

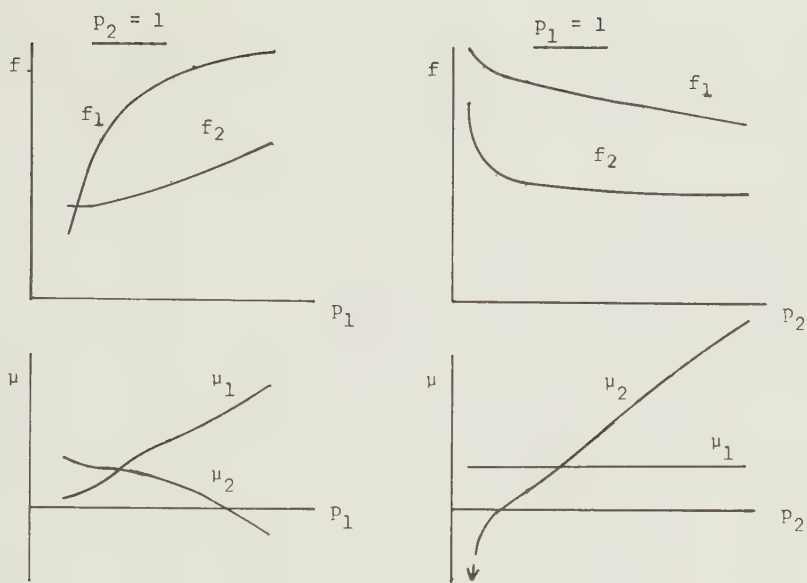


Fig. 3.2

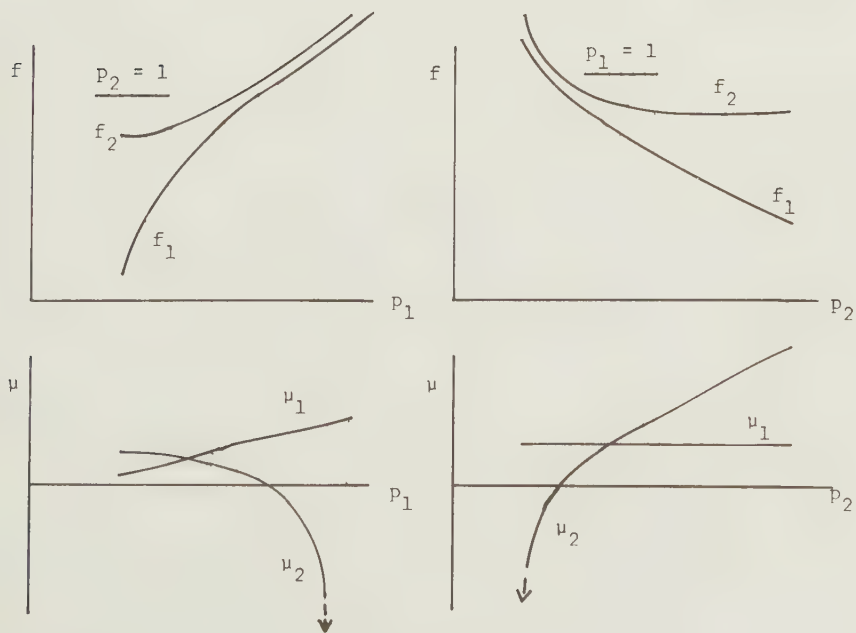


Fig. 3.3

TABLE 3.2

Same values of constants as in 1, except $e_1=2.5 \cdot 10^{-4}$, $e_2=1.25 \cdot 10^{-4}$

<u>$P_1=1$</u>										Sign
P	W_1	W_2	f_1	f_2	Y_1	Y_2	μ_1	μ_2	Δ	Rent (U)
3.0	4782.8	1060.5	137.0	336.8	655.4	714.4	0.791	2.529	+	2324.7
2.7	4607.0	1020.0	169.1	333.9	779.2	681.2	0.783	2.210	+	2115.4
2.4	4444.9	975.0	200.6	332.8	891.8	649.0	0.775	1.887	+	1915.9
2.1	4296.2	924.8	231.8	333.5	995.7	616.9	0.767	1.559	+	1726.0
1.8	4163.5	865.2	263.3	337.2	1096.1	583.5	0.760	1.222	+	1545.9
1.5	4052.1	789.7	296.1	345.3	1199.7	545.4	0.753	0.867	+	1376.4
1.2	3978.4	679.3	332.9	362.8	1324.3	492.9	0.749	0.464	+	1220.1
1.0	3966.1	567.8	362.3	384.3	1436.9	436.4	0.748	0.119	-	1126.7
0.9	3980.7	489.8	380.0	400.8	1512.5	392.7	0.749	-0.121	-	1085.1
0.7	4093.6	240.7	428.1	457.7	1752.6	220.3	0.756	-1.377	-	1021.0
0.6	4237.7	17.5	465.9	511.4	1974.4	17.9	0.764	-28.004	-	1007.9

<u>P₂=1</u>										
1.4	4151.2	16.1	477.1	506.2	1980.4	16.3	1.159	-30.020	-	1805.6
1.3	4090.9	164.8	447.4	472.7	1830.4	155.8	1.056	-2.034	-	1615.2
1.1	4004.3	436.8	390.3	413.0	1562.7	360.7	0.850	-.145	-	1276.5
1.0	3966.1	567.8	362.3	384.3	1436.9	436.4	0.748	0.119	-	1126.7
0.8	4008.2	811.7	296.0	338.2	1186.6	549.0	0.551	0.384	+	864.1
0.6	4240.9	1054.9	206.2	304.1	874.3	641.5	0.364	0.526	+	655.9
0.5	4500.0	1187.6	140.6	293.7	632.8	697.7	0.278	0.579	+	579.7
0.4	4960.6	1342.5	44.3	291.5	219.7	782.8	0.198	0.628	+	534.8

The right hand sides of Fig. 3.2 and 3.3 (upper part of Tables 3.1 and 3.2) show that fishing effort for the predator species is a decreasing function of its price when it falls below a certain value. There are two reasons for this: In the first place, an increase in the price of the predator has the effect of increasing the value of a prey fish that is left unexploited as mentioned above. The optimal level of prey stock therefore increases as the price of the predator increases beyond a certain value, so that any given stock of predator fish yields a larger surplus production than before. Second, and more importantly, a part of the social value of every predator fish caught derives from its detrimental effect on the prey stock. For a "low" relative price of

the predator it becomes desirable to exploit this species in order to increase the yield from the prey species and less for the sake of benefitting consumers directly. To this end it is optimal to subsidize the exploitation of the predator, implying that a marginal predator fish caught is of greater social value than the price consumers are prepared to pay for it.

Considering the case when the optimal tax on catch is zero ($\mu_1=0$) we arrive at the following interpretation: A fish has no value as an input into the ecological system when the value of the impact on the production constraint of a marginal increase in its stock is zero. This follows from Eq. (3.18'); μ_1 is zero only if the sum of the last two terms is zero. This is also implied by setting Eq. (3.27) equal to zero:

$$(3.32) \quad \gamma_1 \cdot (\partial H_1 / \partial W_1) \cdot (-\partial G_1 / \partial W_2) + \gamma_2 \cdot (\partial H_2 / \partial W_2) \cdot (\partial G_1 / \partial W_1) = 0.$$

Multiplying by dW_2 , which denotes a small decrease in the stock of the predator species, and dividing by $\partial G_1 / \partial W_1$, gives

$$(3.32') \quad \gamma_1 \cdot (\partial H_1 / \partial W_1) \cdot \frac{(-\partial G_1 / \partial W_2)}{(\partial G_1 / \partial W_1)} \cdot dW_2 + \gamma_2 \cdot (\partial H_2 / \partial W_2) \cdot dW_2 = 0$$

Now, the increase in the stock of species 1 implied by the condition that the growth rate of that species be maintained, is given by differentiating the growth function, setting the result equal to zero:

$$(3.33) \quad (\partial G_1 / \partial W_1) \cdot dW_1 + (\partial G_1 / \partial W_2) \cdot dW_2 = 0.$$

Inserting Eq. (3.33) into Eq. (3.32') gives

$$(3.32'') \quad \gamma_1 \cdot (\partial H_1 / \partial W_1) \cdot dW_1 + \gamma_2 \cdot (\partial H_2 / \partial W_2) \cdot dW_2 = 0,$$

which is equivalent to Eq. (3.18') for $\mu_2=0$. Eq. (3.32'') says that the net social value of relaxing the production constraint for the prey by decreasing the predator stock equals the net social value of the simultaneous relaxation of the production constraint for the predator itself. When this holds, the value of a predator fish left unexploited is nil, and the social value of a predator fish caught equals the price consumers are prepared to pay for it.

3.5 Concluding Remarks

Ecological interdependence and other inter-species relations thus lead to conclusions that differ in nature from those obtained when only one species is considered in isolation. It is no longer necessary that the future be discounted in order that the optimal rate of exploitation exceed maximum sustainable yield level; this may happen with respect to predators when the relative price of the prey is sufficiently high. Open access to a common-property fishery may then imply underfishing rather than overfishing of predators and other species whose presence is a source of external diseconomies, and it may

be optimal to subsidize the competitive fishery to encourage exploitation of such species.

Inter-species relations, whether they make themselves felt through the growth function or the production function or both, have--perhaps important--an impact on the optimal rate of exploitation. They must therefore enter into the calculating mind--or machine--of the fisheries' manager, but the competitive fisherman has no incentive to take them into account, unless forced to through corrective taxes/subsidies, as he wields no power over the stock size of any species. The need for central management is particularly obvious when an increase in the relative price of a given species implies a decreased optimal fishing effort for that species, whereas the reaction of competitive fishermen will be the opposite.

Chapter 4

THE NORTH ATLANTIC COD FISHERIES: A CASE OF INEFFICIENT EXPLOITATION

4.1. Introduction

We now come to the more applied part of this study; that which deals with the North Atlantic cod fisheries. They have for a long time attracted the interest of fishery biologists and national authorities. A long record of data gathering and analysis has been established under the auspices of two international organizations dealing with the Atlantic fisheries, The International Council for the Exploration of the Sea (ICES) and The International Commission for the Northwest Atlantic Fisheries (ICNAF).

But when it comes to fisheries management, the record of international cooperation is less impressing. The only management measures that have been agreed on internationally are mesh size regulations and, as recently as 1972, catch quotas in the Northwest Atlantic. Regulation of fishing effort, whether in quantitative terms or by taxation (cf. Chapter 3) is totally absent. Nevertheless, fishery biologists have repeatedly warned of overexploitation, and their analyses show that fishing mortality has for two decades or more exceeded the level required to take maximum sustainable yield from the Northeast Atlantic cod stocks. (Clayden 1972, Anon. 1972.)

As the North Atlantic cod stocks have been common property to which access has been free, one would expect overexploitation in the sense that the present value of profits could be increased by reducing fishing effort (cf. Chapter 2). It is, however, not enough merely to compare the actual rate of exploitation to that which maximizes sustainable yield. From an economic point of view it is necessary to consider fishing costs and time preference explicitly, in order to calculate the optimal rate of exploitation. From Chapter 2 we know that a "high" discount rate together with "low" fishing costs may cause the optimal rate of exploitation to exceed that which maximizes sustainable yield. Although the discounting of future profits is no more relevant than the maximization of stationary rent unless there is a single authority to manage the fisheries, we find it nevertheless meaningful to consider the following question: Would any "reasonable" combination of cost per unit of effort and discount rate imply that the recent rate of exploitation in the North Atlantic cod fisheries is in fact compatible with maximizing the present value of rents? If so, it would go some way to explain the apparently complacent attitude adopted by most, if not all, national authorities with direct interests in these fisheries, as they would then have an ample reason to be contented with status quo.

We shall in this chapter take a long term view and assume a constant price of fish and opportunity cost of fishing effort. It will be assumed that the optimal rate of exploitation is stationary, and we shall therefore compare alternative stationary states, but even consider explicitly the transition from one stationary state to another, which will be important in the case of discounting.

Recently, fishery biologists have made two comprehensive investigations of the North Atlantic cod stocks, one by A. D. Clayden at the Fisheries Laboratory, Lowestoft, England, and the other by a joint ICES/ICNAF working group under the chairmanship of D. J. Garrod, also at Lowestoft (Clayden 1972, Anon. 1972). We shall rely on these studies as sources of data and refer to them as the Clayden and the working group report respectively. As they differ with respect to certain estimates and identification of unit stocks we shall use both, not being in the position to judge their relative merits from a biological point of view, and examine whether or not they lead to similar conclusions. Some estimates have been modified by us; see Appendix to this chapter for details.

Both Clayden and the working group used the same yield model, based on the Beverton-Holt approach. This model will also be used here to calculate the present value of profits and find the optimal rates of exploitation by simulations. We shall therefore begin by explaining the Beverton-Holt model, the simplifying assumptions behind it (Section 4.3) and a simple production function of the fishery based on the model (Section 4.4). In Section 4.5 the stationary yield curve is discussed. It will be explained how the curve is affected by gear selectivity, natural mortality of fish and the size of young cohorts of fish recruited to the stock. We shall then discuss the implications of the shape of the stationary yield curve for short term efficiency and the transition to a stationary state which is efficient in the long run.

In Section 4.6 we discuss our approach to an economic analysis of the data presented in the two biological studies mentioned above. In Section 4.7 we present the results stock-by-stock.

4.2. A Beverton-Holt Yield Model

Consider a cohort, alias year class, of fish that are hatched or "recruited" at time $t = t_r$. At every moment they face a certain mortality risk, owing to natural predation and fishing. As these are mutually exclusive events, the total weight (W) of the year class of age $h = t - t_r$ is

$$(4.1) \quad W_h = N_h \cdot w_h = R \cdot e^{-\int_{t_r}^t (F_{\xi} + M) d\xi} \cdot w_h$$

where N_h is the number of fish of age h ,
 w_h is the weight of a representative fish of age h ,
 R is the number of fish recruited at $t = t_r$,
 F_ξ is instantaneous fishing mortality at time ξ ,
 M is natural mortality, taken to be constant for reasons to be explained later.

Suppose now that time is divided into intervals of equal length, e.g. years, and that fishing mortality is constant throughout each year, but permitted to vary from one year to another. Instead of the integral in Eq. (4.1) we will then have a sum of a number of terms. At each instant the year class will be suffering some gross loss of biomass as fish are dying; this loss will be equal to $\dot{N}_h \cdot w_h$ for a year class of age h . The total loss of biomass in the interval t_1 -- t_2 will then be equal to

$$(4.2) \quad -\int_{t_1}^{t_2} \dot{N}_t - t_r w_t - t_r dt = -N_t - t_r \left[t_1 \cdot \bar{w}_h \right]^{t_2}$$

by the mean value theorem of integrals, $\bar{w}_h$ being the mean weight of a fish of this particular year class in the interval t_1 -- t_2 .

We are interested in the yield (Y) in the interval t_1 -- t_2 , which is equal to that part of the loss of biomass which is due to fishing. The yield is therefore obtained by multiplying Eq. (4.2) by $F_h/(F_h + M)$, where F_h is the fishing mortality prevailing in the interval t_1 -- t_2 :

$$(4.3) \quad Y_h = \frac{F_h}{F_h + M} \cdot \left[R \cdot \bar{w}_h \cdot (1 - e^{-\sum_{j=1}^{h-1} (F_j + M)}) \cdot e^{-\sum_{j=1}^{h-1} (F_j + M)} \right]$$

Note that $\bar{w}_h$, the mean weight of fish of age h , is not independent of fishing mortality in the interval t_1 -- t_2 . The higher fishing mortality is the fewer fish will be present at any moment $t_1 + \tau$, where τ is an arbitrarily short interval. The mean weight of a representative fish in the interval t_1 -- t_2 is therefore a decreasing function of fishing mortality prevailing in that interval, given that the weight of individual fish increases with age. We shall however ignore this and regard the mean weight at age as a fixed parameter, denoted by w_h . While this is bound to result in some loss of accuracy, it will not be of sufficient magnitude to affect our conclusions. A typical growth curve for individual codfish is shown in Fig. 4.1. The curve has an inflection point at a low age of fish, beyond which it grows at a decreasing rate towards an asymptotic weight.¹

1 On growth in cod, see for example Beverton and Holt (1957).

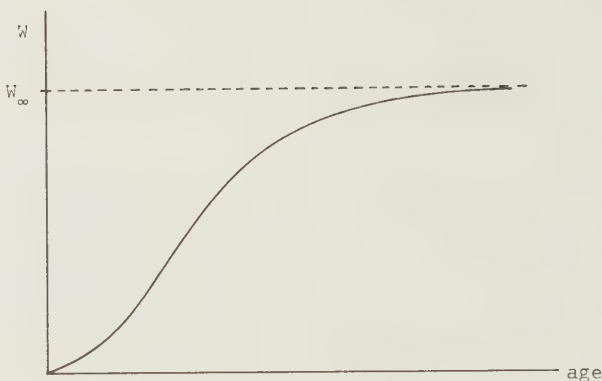


Fig. 4.1

At any point in time, a "stock" of fish consists of a number of year classes recruited at discrete intervals, so the total yield from the stock in period t is the sum of yields from each year class:¹

$$(4.4) \quad Y_t = \sum_{i=t-\lambda}^{t-1} \frac{\epsilon_{t-i} \cdot F_t}{\epsilon_{t-i} \cdot F_t + M} \cdot (1 - e^{-(\epsilon_{t-i} \cdot F_t + M)}) \cdot e^{-\sum_{j=i+1}^{t-1} (\epsilon_{j-i} \cdot F_j + M)} \cdot R_i \cdot w_{t-i}$$

where λ is the life span of the fish; recruitment is assumed to occur instantaneously at the end of each period. The definition of life span serves the purpose of economizing on calculations; when the number of survivors in a year class has fallen to some small fraction of the original number of recruits, it may be regarded as forever lost. The parameter ϵ_h is the fraction of overall fishing mortality, determined by fishing effort, that fish of age h encounter. The role of this parameter is to account for the fact that fish are gradually recruited to the fishable stock. Typically, ϵ_h gradually increases with age from 0 to 1, cf. Fig. 4.2.

4.3. Important Assumptions Behind the Beverton-Holt Model

The most important assumption behind the Beverton-Holt model is that of

¹ This variant is due to Clayden (1972).

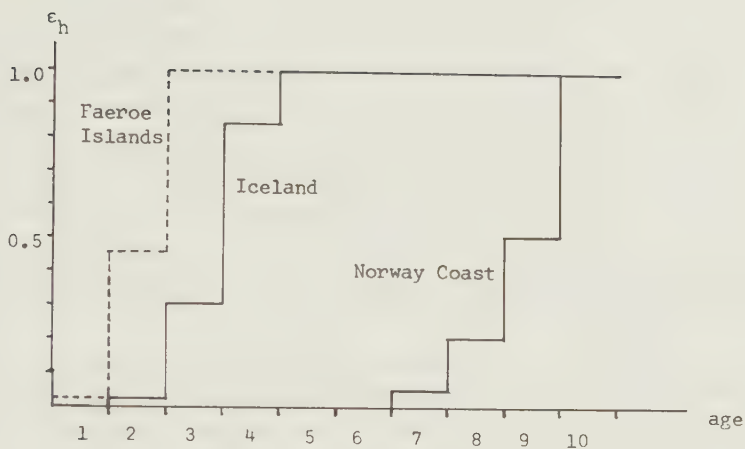


Fig. 4.2

constant environmental conditions for adult fish. This assumption manifests itself in the constancy of the parameters M (instantaneous natural mortality) and w_h (weight at age h). Intuitively, both of these would be expected to depend on the density and age composition of the fish population and thereby on lagged values of fishing mortality. Less density and lower average age of the population might result in either a greater or smaller natural mortality risk; as a lower number of smaller fish are being preyed on the mortality risk might increase, whereas less competition for a given supply of food would be expected to result in less natural mortality due to improved living conditions for the average fish. Less density would therefore also be expected to imply increased rate of growth of individual fish. Despite these shortcomings the Beverton-Holt model appears to have given rather satisfactory results with respect to a number of fisheries.

Application of the Beverton-Holt yield model clearly requires that the age of individual fish can be determined. This is possible with respect to many species, especially long lived ones in temperate waters, as the seasons leave marks or "rings" in their scales and otoliths. Weight at age may thus be estimated from a sample of fish. Besides the variation of the weight of individual fish of a given age around the mean, any possible density-depen-

dence of growth will also be obscured by the fact that it varies in response to fluctuations in environmental conditions, the most important of which seem to be variations in temperature.¹ There is some evidence, however, of density-dependent growth in young codfish (Schopka 1972). Age composition analysis also facilitates the estimation of mortality; by studying how the age composition of catches changes from one year to another it is possible to estimate annual survival rates and calculate instantaneous mortality rates on the assumption that they are constant throughout each year. As this estimate, Z , is the sum of instantaneous natural and fishing mortality ($Z = F + M$), it follows that it is not possible to observe natural mortality directly, which is one reason why it is difficult to uncover any density dependence of this parameter.²

It is also possible, however, that the assumption of non-density dependent weight at age is a good approximation of reality, and that availability of food is not in fact a limiting factor for the growth of the post-recruit population. It is quite conceivable that the number of recruits is controlled in such a way that the size of the post-recruit population is always less than the maximum that could be sustained by the environment, with natural mortality risk due to predation and senility keeping the stock from increasing beyond a certain limit. It is certain that the egg and larval stages are the critical periods of life for cod and many other species, with extremely variable natural mortality owing to fluctuating environmental conditions.

This leads us to consider the parameter R , the number of recruits to a given year class. A very straightforward hypothesis is to regard it as a function of the parent population and thus indirectly of lagged values of fishing mortality. A stock-recruitment relation may easily be incorporated into the model (cf. Walters 1969), but whether or not any such relation of significance exists is another question. Garrod (1967) has studied this problem with respect to the Arcto-Norwegian cod and presented the diagram shown in Fig. 4.3. It is immediately obvious that non-stock-dependent factors have a highly significant influence on recruitment, at least over a wide range of stock size. No one of course denies that there must be a critical range in which the number of spawners is so small as to seriously reduce recruitment, but there is no evidence so far that any stock of North Atlantic cod has been diminished to such

1 Cf. C.C. Taylor: Cod Growth and Temperature, Journ. Conseil Vol. 23, pp. 366--370, 1959, and the subsequent exchange between him and S. Holt in the same journal Vol. 24, pp. 374--376 and Vol. 25, pp. 223--227.

2 On the estimation of mortality see W.E. Ricker: Handbook of Computations for Biological Statistics of Fish Populations, Bull. Fish. Res. Bd. Canada 119, 1958.

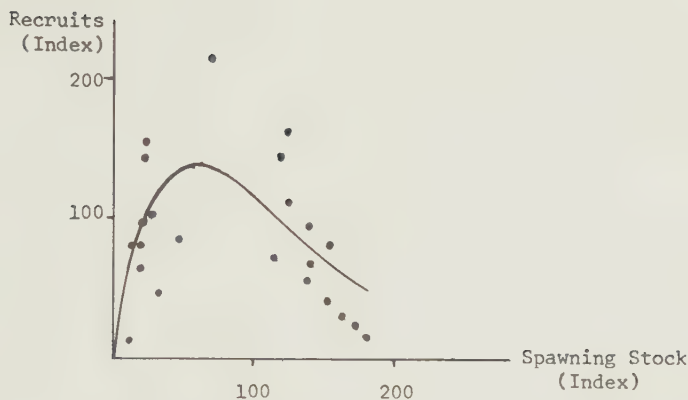


Fig. 4.3

a low level, with the possible exception of the Arcto-Norwegian stock.

The right hand side of the recruitment curve in Fig. 4.3 indicates that a large spawning stock has a negative effect on the number of recruits. The reason could very possibly be that the omnivorous adult codfish prey on their eggs and larvae.

A hypothesis consistent with Fig. 4.3 is that the average number of recruits is constant and seemingly independent of the parental stock over a wide range, excluding extreme levels. Recently, J. A. Gulland (1971) has advanced the following explanation: Suppose that the number of eggs produced is proportional to the size of the spawning stock. It is then necessary that the survival rate of eggs increase as the spawning stock decreases in order to maintain a constant number of recruits. A very slight change in egg mortality would be sufficient for this to happen. Fish generally produce an immense number of eggs, whereas the survival rate is extremely low. If, say, the mortality of eggs is 99.998% and the survival rate therefore 0.002%, a slight change in mortality, that is, to 99.996%, would double the survival rate. Such a change could very possibly be the result of halving the size of the spawning stock, given that adult fish prey on their eggs. The relation between stock and recruitment is undoubtedly more complex than this simple example purports, but as it still remains to be uncovered we shall proceed on the assumption that the average number of recruits is independent of stock size and the rate of exploitation.

One reason why it is difficult to detect any relation between the spaw-

ning stock and the number of recruits is that recruitment fluctuates widely from one year to another as a result of changing environmental conditions. The cod stocks of the North Atlantic are to a high degree characterized by such fluctuations, which have no counterpart in variations in the size of the spawning stock. Research on the survival of cod eggs indicates a heavy influence of environmental factors that may differ from place to place. In the Barents Sea it seems to be temperature at a critical age that is most important for egg survival, while in the Baltic Sea it appears to be the salinity of the water.¹ In Chapter 5 we shall consider the impact of the variations in abundance generated by these fluctuations in recruitment on optimal fishing, whereas in this present chapter we are interested in average long term conditions and assume therefore that annual recruitment is constant.

4.4. A Production Function Based on the Beverton-Holt Model

The connection with the fishing industry is provided by the fishing mortality parameter (F). The activities of the fishing fleet will add to the mortality risk that a fish encounters, and it is necessary to relate this fishing mortality to some measure of the activities of the fishing fleet in order to be able to use the Beverton-Holt model for the purposes of economic analysis. As much research by fishery biologists is aimed at studying the response of a given fish population to a change in mortality due to fishing, they have long attempted to find a measure of fishing effort that is directly proportional to the mortality it generates. But defining fishing effort in terms of the risk for fish to encounter the fishing gear need not be satisfactory for the purposes of economic analysis, as it excludes such auxiliary activities as search, processing at sea and transportation. (Cf. Chapter 2.) A study of a "first-best" definition of effort from the economist's point of view with respect to the North Atlantic cod fisheries is, however, beyond the scope of our undertaking. We shall instead proceed on the basis of the biologists' definition of effort, as it is reasonably well established and standardized data are available. As a further defense it may be added that effective fishing effort in the biologist's sense may very possibly be a good proxy for total effort in the economist's sense. This would require a constant proportion between on the one hand time spent trawling, and on the other time spent searching, processing and sailing between port and fishing grounds. This is not so unrealistic as it may at first appear, especially not with respect to smaller trawlers without sophisticated storage and processing facilities, as fish deteriorate quickly unless they are filleted and frozen, and only limi-

¹ Cf. Proceedings from a Symposium on stocks and recruitment, edited by B.B. Parrish (1973).

ted provisions can be carried on each trip without supporting craft.

A study by Gulland (1956) of the English trawl fisheries showed that the fishing power of a trawler in the 150--900 GRT size class was approximately linearly related to its size. The standard measure of fishing effort in the trawl fisheries would therefore be hours trawling multiplied by the size of the vessel.¹ Such standardized primary data on effort in the North Atlantic cod fisheries do not exist, however, for two reasons: (i) Different technologies are used; e.g. long line, gill nets, otter trawl etc., each of which requires its specific measure of effort; these are therefore not directly comparable. (ii) This is a highly international industry, and even though two nations use the same technology they may nevertheless differ in their measurement of effort. In his study of these fisheries, Clayden (1972) attempted to standardize the national data on effort, on the assumption that two units of effort must yield the same catch in case they are applied on the same ground at the same time. All data on effort are thus converted to English fishing hours, adjusted for average vessel size. We shall define a unit of effort as one million English ton-hours of fishing (MTH).

As instantaneous yield is equal to instantaneous gross loss of biomass due to fishing, that is, equal to $F \cdot N \cdot w$, Eq. (2.2) implies

$$(4.5) \quad F = q \cdot f.$$

Although one may have succeeded in finding a measure of fishing effort that a priori seems likely to be linearly related to fishing mortality, the exact relation is of course an empirical question. In Chapter 2 it was asserted that the availability coefficient (q) might depend on both fishing effort and stock density. As all estimates of biomass are imprecise, we shall not pursue the question whether or not the availability coefficient depends *oet. par.* on stock density. This relation would also be subsumed in an estimate of the relation between fishing mortality and fishing effort for alternative stock equilibria, as in that case stock is a function of effort. One would then estimate the relation

$$(4.6) \quad \frac{dq}{df} = \frac{\partial q}{\partial f} + \frac{\partial q}{\partial W} \cdot \frac{\partial W}{\partial f}.$$

Bearing in mind that we are considering the long term relation between

1 This measure of effective fishing effort has been criticized in an Icelandic study, on the following grounds: Some skippers prefer to drag the trawl while searching for fish, whereas others rely more on fish finding equipment and throw out the trawl only when they have detected a major concentration of fish. The implication for the trawling hour as a measure of effective fishing effort is obvious. Cf. Brádabirgdaskýrsla um adgerdarrannsóknir á útgerð togskipa, Fiskifélag Íslands og Rannsóknarstofnun Háskólans, Reykjavík, July 1969.

effort and the availability coefficient, it is highly plausible to assume that it is in fact constant and independent of effort. This would be true if the fish are always to be found in the same area, A, at the same time of the year, being uniformly distributed throughout that area. If then subarea a is randomly selected for trawling, the catch taken would always be a constant proportion of the total stock in area A. As the fish do not redistribute themselves instantaneously between successive hauls, there is every reason to expect that the availability coefficient--i.e. the proportion of the total stock in area A being taken--would in fact decrease in response to repeated trawling in subarea a in the short run of days and weeks. In the longer run of months and years, one may expect the relative distribution of fish and fleet to stay more or less constant, as the fleet will move on when the population in subarea a is being thinned out, so that the availability coefficient will tend to be a constant in the long run.

Circumstances which would dictate that the availability coefficient depended on fishing effort might be as follows: If the diminished stock inhabits an area smaller than A and is uniformly distributed throughout that area, stock size and stock density are no longer equivalent. Trawling of area a will then take a larger proportion of the total stock, and the availability coefficient will thus be an increasing function of effort. On the other hand, if a part of area A is unsuitable for fishing and if the fish redistribute themselves very slowly in the area, the relative distribution of fleet and stock will not remain uniform, and the availability coefficient will be a decreasing function of effort.

Clayden, on whose study we shall rely for data and estimates, assumes a linear relation between fishing effort and mortality. His material includes independent estimates of these variables, but only in one case out of nine (Barents Sea cod) does he obtain a significant linear regression of Z on f. It does not necessarily follow that this hypothesis should be rejected. It would be nonsense to believe that fishing mortality was *not* in some way related to fishing effort, and non-linear relations do not appear to give a better fit. Next to the Arcto-Norwegian stock the data from the international cod fishery off Iceland contain the longest time series of estimates of mortality; our attempts to find a significant non-linear relation between fishing effort and mortality proved unsuccessful however.¹ Two non-linear relations were tried

¹ The term "international" refers to that part of the fishery which is conducted on an all year round basis, mostly by English trawlers, in contrast to the Icelandic seasonal fishery, which concentrates on the spawning migration of fish.

(note that $Z = F + M$):

$$(4.7) \quad Z = k + af + bf^2,$$

and

$$(4.8) \quad Z = k + bf^a, \text{ or } \log(Z-k) = \log b + a \cdot \log f$$

both of which imply that the availability coefficient is a function of effort, $q = a + bf$ and $q = bf^{a-1}$ respectively. A multiple regression of Eq. (4.7) resulted in an insignificant estimate of b and $k < 0$, which would imply a negative natural mortality and must be rejected as nonsensical. A linear regression of Eq. (4.8) was tried for three assumptions about k , 0.1, 0.2 and 0.3. This yielded the following estimates of a : 0.55, 0.65 and 0.89, but as it was in no case significantly less than one and R^2 in all cases less than 0.16, the hypothesis of a constant availability coefficient was not rejected.

The period to which the estimates of mortality refer (1956--1966) was one of unprecedented development in electronics and its application to marine search, both for military and fishing purposes. One would expect that a million ton-hours of trawling in 1956 would hardly be equivalent to the same figure ten years later, as fishermen would in that later year have been better able to detect a major concentration of fish before throwing out the trawl, thus increasing the efficiency of each haul. An attempt to account for technological progress by estimating the relation

$$(4.9) \quad Z = M + bf + d \cdot (t - 1946),$$

where t is the year to which the observation refers gave an insignificant but negative estimate of d , which is certainly contrary to expectation. It is possible that the linear relation between the size of vessels and their fishing power discovered by Gulland (1956) in fact reflected technological progress rather than the effects of sheer size, as would be the case if the larger trawlers in general represented a newer and superior technology than the smaller ones. Technological progress would thus be embodied in our data on fishing effort, as the average size of vessels has increased throughout the whole period considered (1956--1966). It is also possible that electronic equipment saves cost without increasing the efficiency of each haul, as it makes it easier for the skippers to avoid areas with a rough bottom that damages the gear.

Having failed to arrive at anything more convincing, we shall follow Clayden's approach and assume a constant availability coefficient, not only with respect to Iceland cod, but other stocks as well. Since a linear regression of Eq. (4.5) is insignificant in all cases except one it is of little help in estimating natural mortality (the constant, k , in the regression equation). Clayden and others who have studied the North Atlantic cod fisheries (Anon. 1972) assume instantaneous natural mortality of 0.2; this assumption

will for the most part also be made here. The availability coefficient may then be estimated by a linear regression of Eq. (4.5) with a given constant term.

A simulation of the international cod fishery off Iceland in the period 1946--1968 is shown in Fig. 4.4, with $q = 0.0022$ and $M = 0.2$. Whether or not the result is satisfactory is a matter of judgement, but it is necessary to point out that any deviation between actual and simulated mortality will generate autocorrelation in the residual terms, (i.e. the difference between observed and simulated catches), because the yield model incorporates 12 year classes in any single year. Too high simulated mortality in any one year will therefore mean that all year classes fished during that year will be reduced too much, and a correct simulated fishing mortality in subsequent years will result in too small catches. Such deviations may be due to stochastic fluctuations in the availability coefficient caused by weather, currents, temperature in the sea etc. Secondly, they may be due to fluctuations in the seasonal distribution of the fishing fleet. The availability coefficient fluctuates from one season to another, even though its pattern and thereby also average availability may be constant from year to year. If fishing effort is heavily concentrated in the season when the availability coefficient is high, it will

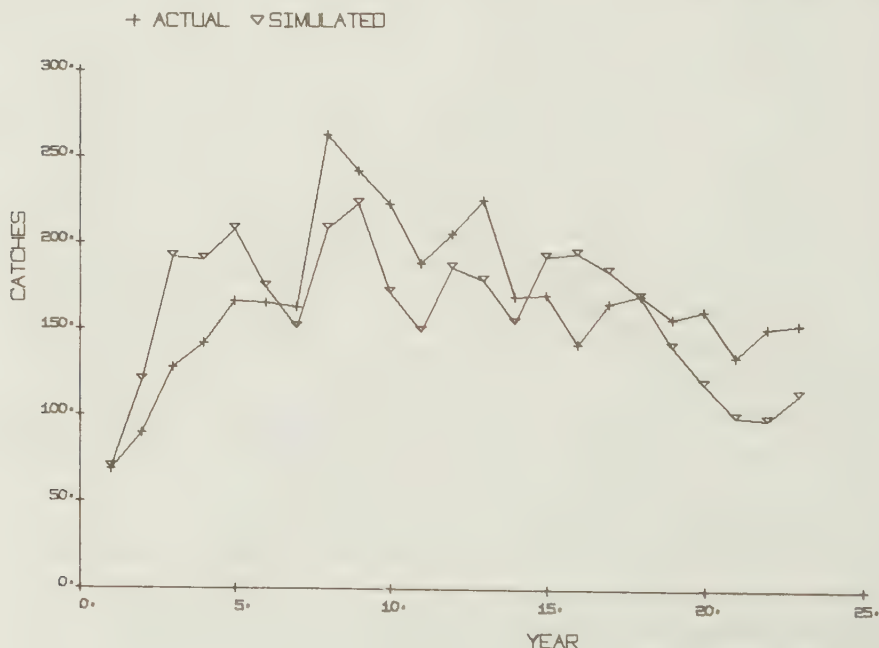


Fig. 4.4

have a larger impact on fishing mortality than the same amount of effort that is spread evenly over the whole year. Since annual data on effort are used, it is assumed to be evenly distributed throughout each year. In reality the seasonal distribution of fishing may vary in a way which is not perfectly synchronized with the variations in the seasonal pattern of availability, resulting in a difference between actual and simulated fishing mortality.

In the subsequent simulations we shall assume that the cost per unit of effort is constant. This greatly simplifies the analysis and is of little relevance for the following discussion of long term optimum. Since there is only one relative price in the model we shall find it convenient to use fish as a numéraire commodity and take one thousand metric tons of life weight fish (TMT) as a unit of account. Note that the linear relation between fishing effort and fishing mortality in effect makes one a measure of the other, and we shall use the two as synonyms in the following discussion.

4.5. The Sustainable Yield Curve

If the biological parameters and gear selectivity are known, Eq. (4.4) makes it possible to derive the sustainable yield curve, that is, yield as a function of stationary fishing mortality for a given, average recruitment. For later reference, let us briefly review how the shape of the yield curve is affected by changes in gear selectivity, number of recruits and natural mortality.

Since the age composition of the stock is constant under stationary conditions, the total life-time yield from a year class of fish is equal to the annual yield from the whole population. In absence of fishing the biomass of a year class of fish (W) will be at time t (cf. Eq. 4.1):

$$(4.10) \quad W_t = R \cdot e^{-M \cdot (t-t_r)} \cdot w_{t-t_r}$$

and its rate of change will be

$$(4.11) \quad \dot{W}_t = -M \cdot R \cdot e^{-M \cdot (t-t_r)} \cdot w_{t-t_r} + \dot{w} \cdot R \cdot e^{-M \cdot (t-t_r)} = \left(\left(\frac{\dot{w}}{w} \right)_{t-t_r} - M \right) \cdot R \cdot e^{-M \cdot (t-t_r)} \cdot w_{t-t_r}$$

As the relative growth rate of fish ($\dot{w}/w$) is a decreasing function of age beyond a certain "low" age (cf. Fig. 4.1), it follows that the biomass of the year class will be at its maximum at $t = t'$, when $\dot{w}/w = M$, and decline after that. Eq. (4.10) may be shown as a curve in W, t space, which is done in Fig. 4.5.

Assume for simplicity that all fish above a certain age, $t_c - t_r$, are fully

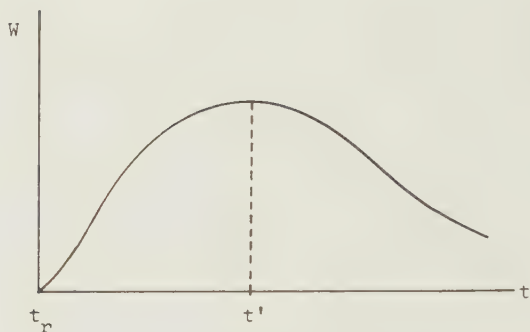


Fig. 4.5

selected by the gear, but younger ones not at all (knife edge selectivity). Since the yield in numbers at any instant is equal to the change in the number of fish due to fishing; that is, FN_t , the total yield from a year class throughout its fishable life span for a given F is equal to

$$(4.12) \quad \int_{t_c}^{t_r + \lambda} F R w_{t-t_r} e^{-(F+M) \cdot (t-t_c) - M \cdot (t_c-t_r)} dt$$

where λ is the life span of the fish. The rate of change of biomass for $t > t_c$ is

$$(4.13) \quad \dot{W}_t = \left(\left(\dot{w}/w \right)_{t-t_r} - F - M \right) \cdot R \cdot e^{-(F+M) \cdot (t-t_c) - M \cdot (t_c-t_r)} \cdot w_{t-t_r}$$

Increasing fishing mortality (F) will thus have two opposite effects on the stationary yield: First, it increases the proportion caught of biomass available at any instant. As $F \rightarrow \infty$ the whole biomass available will be fished instantaneously at t_c . Secondly, as F increases there will be less fish available for any $t > t_c$. If $t_c > t'$, i.e. the fish do not enter the exploitable phase until after the year class has attained its maximum weight, the sustained yield may be raised by increasing fishing mortality ad infinitum, and the sustainable yield curve will have no maximum like curve I in Fig. 4.6, approaching asymptotically a level equal to the biomass available at t_c . If on the other hand $t_c < t'$, then the yield curve will have a maximum. For three different values of fishing mortality, $F_1 < F_2 < F_3$, the year class biomass will evolve through time as the curves labelled $W(F_i)$ in Fig. 4.7 indicate. As F determines the proportion of biomass that is fished at each instant, the total yield from the year class is the area under the curve labelled $Y(F_i)$. As Fig. 4.7 illustrates, sustained yield may be increased through more intensive fishing up to a point, beyond which the adverse effect of high fishing morta-

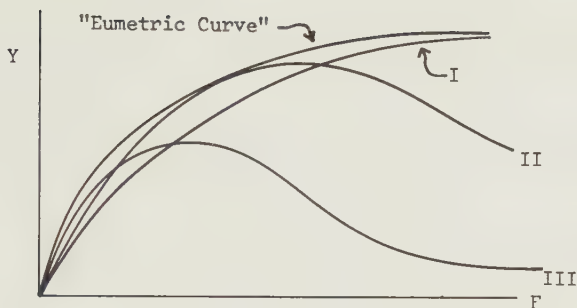


Fig. 4.6

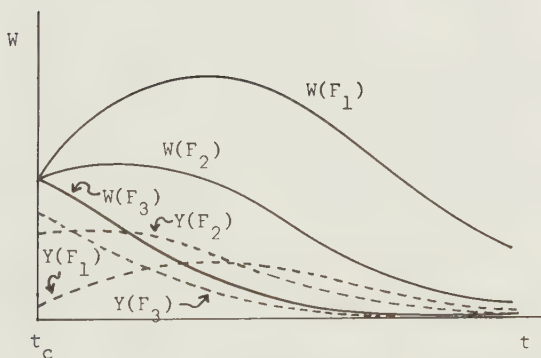


Fig. 4.7

lity on future availability of fish predominates. The sustained yield curve will therefore look like curve II in Fig. 4.6. The assumption of exogenous recruitment ensures that the yield curve will not fall back to the F -axis, but instead approach the total biomass of the year class at t_c asymptotically.

If the age of recruitment to the fishery ($t_c - t_r$) were lowered further, it would give rise to yet another sustainable yield curve labelled III in Fig. 4.6. Its asymptotic level is lower than for curve II, as the year class biomass is less at the time of recruitment to the fishery in this case than for curve II. Curve III however rises more steeply for low levels of fishing mortality, because the (stationary) yield increases more quickly when effort is increased from a "low" level the greater is the number of year classes being fished simultaneously. Third, the maximum of curve III is lower than that of curve II, because, for any given fishing mortality, each age group will weigh

less at any $t > t_c$ the lower is the age of recruitment to the fishery.

If we imagine a cost curve being drawn in Fig. 4.6 and the stationary flow of profits is to be maximized, this would happen at a point on a yield curve where the vertical distance from the cost curve is as large as possible. The curve combining all such points (the envelope to all yield curves) is called the "eumetric" yield curve. Optimizing both gear selectivity and fishing effort clearly means selecting the point on the eumetric yield curve that maximizes profit. The theory of eumetric fishing was developed by Beverton and Holt (1957), and its economic implications discussed by Turvey (1964).

From Fig. 4.6 it is clear that the optimal age of recruitment to the fishery is a decreasing function of cost per unit of effort. This may be explained as follows: A "high" cost per unit of effort implies a "low" optimal fishing mortality. The year classes will therefore not be severely decimated through fishing, and it is important to fish "many" year classes simultaneously in order to achieve high yields per unit of effort. On the other hand, if the cost per unit of effort is "low" and optimal fishing mortality "high", the year classes will be quickly decimated as soon as they grow beyond the age of recruitment to the fishery. If that age is low, only very few fish will attain the age when the natural growth of the year class is equal to its loss through natural deaths ($t' - t_r$), and the yield may be increased by allowing the year classes to grow to an age not much lower than $t' - t_r$ before being hit by the fishery.

As Eq. (4.11) shows, the age at which the biomass of a year class attains its maximum in the absence of fishing ($t' - t_r$) is determined by the growth rate of a "representative" fish and natural mortality. Consequently, the optimal age of recruitment to the fishery is influenced by those two parameters; fish that grow fast or are exposed to high natural mortality will have a low optimal age of recruitment to the fishery.

If natural mortality is increased with recruitment and growth rate of individual fish remaining unchanged, the total weight of a year class will at any age be less than otherwise. The maximum of the biomass curve in Fig. 4.5 will be displaced to the left, but the maxima of the yield curves (Fig. 4.6) will be displaced to the right, which is the same thing as saying that the fishing effort required to take the maximum sustainable yield for any given selectivity of gear will be increased. To understand this, consider what happens if natural mortality is increased, with fishing mortality and gear selectivity remaining constant. The highest curve ($W(F_1)$) in Fig. 4.7 would with a sufficiently large natural mortality have no maximum, and fishing mortality could then be increased towards infinity with the catch approaching the total biomass of the

year class at t_c , which is to say that the yield curve has no maximum. If on the other hand recruitment increases with mortality and gear selectivity held constant, this means that the weight of a year class at any age is increased, but the relative rate of change of biomass remains unaffected (cf. Eq. 4.11). This would be equivalent to changing the scale of the y-axis in Fig. 4.5 and 4.7. Therefore, the maxima of the yield curves in Fig. 4.6 still correspond to the same values of F as before, but these curves will also be displaced vertically by a certain percentage and their slope will increase in absolute terms for any other values of F .

Consider again the yield function (4.4). Dividing on both sides by R , it shows the average yield per recruit for a given fishing mortality (Y_R). If all parameters except the number of recruits are known, it may be estimated by the ratio $\bar{Y}/Y_R$, where $\bar{Y}$ is the average total yield. It is clear that the higher the natural mortality (M) is, the lower is the yield per recruit, and consequently the higher is the estimated number of recruits for a given average yield.

A sustained yield curve for the international cod fishery at Iceland is shown in Fig. 4.8.¹ It rises rather steeply up to maximum and tapers off

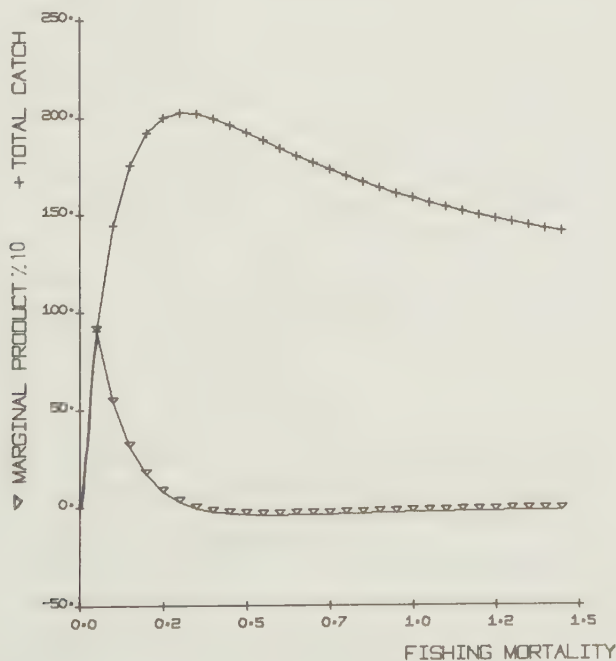


Fig. 4.8

¹ The values of the biological parameters obtained from Clayden (1972).

slowly to the right. This implies that the long run marginal product of fishing effort, $\Delta Y/\Delta F$, where Y and F denote sustained yield and fishing mortality and $\Delta F=0.1$, falls rapidly for low levels of effort to a minimum of - 40.25 TMT for $F = 0.6$, beyond which it approaches the x-axis asymptotically. This follows from the assumption that recruitment is independent of stock size, therefore, a constant number of fish will be recruited to the fishery every year, no matter what the rate of exploitation, and extinction is thus ruled out. We do by no means wish to assert that this holds true for any conceivable rate of exploitation, but it has been argued above that this is a reasonable hypothesis, given the rates of exploitation that hitherto have occurred in the North Atlantic cod fisheries.

The shape of this particular yield curve is roughly representative for the North Atlantic cod stocks, the rest of them have even a less pronounced maximum. With a parabolic yield curve such as in Chapter 2 it could easily happen that the stationary marginal product of fishing effort was well below zero, and considerable long term benefits in the form of increased sustained yield could be obtained by curtailing fishing effort. This will not happen in the cod fisheries as the negative marginal product of sustained effort is nowhere very pronounced. The benefits from reducing effort below its bionomic equilibrium level will therefore almost exclusively depend on the marginal product of effort transferred to the best alternative use; that is, alternative employment opportunities for fishermen and their capital. It is therefore likely that excessive fishing effort in these fisheries should be eliminated slowly, as the opportunity cost of capital already engaged in the fisheries is probably low and fishermen may not be so easily transferable to other occupations in the short run at least. An additional reason for a slow phasing-out of excessive fishing effort is that less effort will always mean less yield in the short term of a few years, although long term yields will increase.

Ex ante, however, capital and labor are mobile. As the sustainable yield is relatively constant for "high" fishing mortality, the bionomic equilibrium is likely to require sustained fishing effort far in excess of maximum sustainable yield level. This suggests that the cod fisheries will be characterized by fishing effort far exceeding the optimum level, constituted by capital and labor that should have been directed to other industries, but which, in the absence of management, has flowed into the fishery, where in the long run it adds less than nothing to the value of goods produced. We shall now turn to consider the question of economic efficiency in these fisheries.

4.6. Economic Assumptions

The fact that fleets from various countries with different wage rates, capital costs and time preference exploit a given stock of fish certainly makes *the* optimum rate of exploitation an ambiguous concept. A detailed investigation of the fishing costs of various national fleets is beyond the scope of this study, but something may still be inferred from the theory of exploitation under common property, reviewed in Chapter 2. If a multi-national but otherwise homogeneous fleet exploits a common property stock in bionomic equilibrium, the cost *in terms of fish* per unit of effective fishing effort--i.e. the effort aimed at entrapping the fish on the fishing ground--must be equal for all national fleets. Consider two stocks of fish that are located in the offshore waters of countries A and B, which are separated by a "great ocean". If the fish stocks are common property and access is open to the exploitation of both, the theory predicts that bionomic equilibrium will be characterized by exploitation to the point where total revenue equals total cost and all economic rent is dissipated. Assuming homogeneous fleets and equal opportunity cost of fishing effort--in terms of fish--for the fishermen in both countries, each country's fishermen would only fish in their offshore waters, since in neither case could it be profitable to cross the great ocean to return with the same catch per unit of effective effort as could be obtained in waters closer to home. Conversely, if say, fishermen from country A were to find it profitable to fish in country B's offshore waters, their opportunity cost would have to be lower than the opportunity cost of fishermen in country B, as fishermen from both countries will have the same catch per unit of effective fishing effort. As fishermen from country A have to spend some time crossing the great ocean in order to apply effective fishing effort off country B's shores, their catches per unit of total effort will be lower than for fishermen from country B. From this follows that "transoceanic" fishing will always take place in one direction only, as fishermen from both countries could not find it profitable to fish in each others waters at the same time.

This very simplified picture distorts the realities of the North Atlantic cod fisheries to some extent, but not beyond recognition. Owing to the seasonal fluctuations in the availability coefficient, it is quite possible that fishermen will find it profitable to fish in different waters at different times of the year. In addition, distant water fleets with elaborate processing facilities perform a more complex function than a fleet that only drags up the fish and sells it fresh in its home port. This makes it more difficult to compare costs between different countries and areas, a problem to which we

shall be returning briefly in Chapter 5. Still, it is true that "transoceanic fishing" is to a large extent a one way affair. North American fishermen do not fish for cod off the west coast of Europe, while the major part of the catches of cod from the waters off the east coast of North America is taken by European fishermen. The Icelanders fish for cod mainly in their home waters.

All the stocks which we shall be considering are common property and exploited by fleets from various countries.¹ Since the data on effort that we use are in terms of English ton-hours fishing, to which data from other national fleets have been converted, we shall take the catch per unit of effort for the English fleet in any given area as being representative of the catch per unit of effort for the entire fleet fishing in that area. These figures are shown in Table 4.1.

In bionomic equilibrium the cost of effective fishing effort--in terms of fish--for homogeneous fleets of different nationalities is equal; i.e. equal to the catch per unit of effort. The relevance of this long-term equilibrium concept is, however, limited in the context of the North Atlantic cod fisheries, due to the exogenous fluctuations in recruitment of young fish. These fluctuations in turn generate fluctuations in catches per unit of effort, with "good" years giving rise to unexpected profits for a given relative price of fish, thus disturbing the bionomic equilibrium. One might expect a countervailing movement of prices, modifying overnormal profits or losses, but any fish market is usually supplied from more than one single area, and, therefore, the relative price of fish should not necessarily be expected to react to "abnormal" catches per unit of effort in one area only. Since the variations in recruitment are stochastic in each area, the changes in catches per unit of effort may also offset each other. We shall therefore proceed as if the relative price of fish can be regarded as a constant.

As the most important determinant of opportunity cost for a mobile fleet fishing in a given area is the value of catches forgone elsewhere, it is not unreasonable to expect that the lowest figures of catches per unit of effort represent a floor below which the opportunity cost of fishing effort in that area should hardly be expected to lie. The opportunity cost of bundles of capital and labor which are uncommitted to the fishery--the cost concept that is relevant here--may even be higher, since a given fishing fleet consists of capital that has been frozen into highly specialized assets, perhaps on the false prospects of the "good old days" when exploitation was light and catches per unit of effort therefore high. We shall therefore take the lowest catch

¹ This is true at any rate of the period to which the data refer, although the Icelandic fishing limits have since been extended.

Table 4.1

Table 4.1												
Catches per unit of effort for the English fleet 1960--1968. Data from Clayden (1972).												
year	Faeroe	Iceland	Norway	Bar. Sea	Bear Island	NW- Greenl.	SW- Greenl.	East Greenl.	Labr./ Newfoundl.	Grand Bank	Labr./ Newfoundl.	Grand Bank
1960	0.373	0.755	0.692	0.744	1.110	1.248	1.278	1.350	0.980	1.360	1.72	1.15
1961	0.212	0.584	0.599	0.808	1.333	2.067	1.209	1.143	2.286	1.275	1.51	1.13
1962	0.258	0.580	0.684	0.944	1.432	1.720	1.440	1.750	2.272	1.374	1.73	0.83
1963	0.302	0.574	0.693	0.864	1.074	2.151	1.528	0.664	1.550	1.556	1.78	1.66
1964	0.313	0.526	0.692	0.578	0.927	2.021	1.548	0.873	0.974	1.371	1.56	1.38
1965	0.403	0.554	0.663	0.658	0.982	1.386	1.965	0.930	1.975	1.210	1.44	1.63
1966	0.618	0.602	0.683	0.749	0.780	1.177	2.113	0.767	1.615	1.125	1.57	1.47
1967	0.617	0.689	0.534	0.806	1.069	1.584	1.930	0.657	1.737	1.884	1.61	1.48
1968	0.546	0.898	0.565	1.158	1.684						1.59	1.44
											1.42	1.16
											1.09	1.09
												1970

per unit of effort figures for the English fleet 1960--1968 as being likely to represent the cost per unit of fishing effort and calculate the optimal rate of exploitation on the basis of this figure, assuming a 10% annual rate of discount to be "realistic". A lower rate of discount would only strengthen any presumptive conclusion of excessive exploitation, as the impact of discounting is to raise the optimal level of fishing effort. This is labelled "case I" in the discussion that follows.

Under case I we examine the question of economic overfishing in the following way: We first calculate the present value of profits that would result from maintaining the "recent" rate of exploitation ad infinitum. The recent rate of exploitation is defined as the average of estimated fishing mortality 1960--1966 when using Clayden's data, but with the period of reference altered to 1966--1970 when using the figures provided by the working group. We then assume that the economic objective is maximization of the present value of profits, given an infinite time horizon, and calculate the optimum fishing mortality and the moratorium that would be profitable to impose on the overfished stock. The length of this moratorium indicates the extent of overexploitation of the initial stock in the model. When using Clayden's figures this initial stock is determined by exposing year classes of average strength to "recent" fishing mortality over their life-span. When using the data provided by the working group we have used its estimate of initial stock in 1960; the moratorium will in that case indicate overexploitation prior to that year. This should not be taken to mean that the recovery of an overexploited fish stock should necessarily be effectuated by bringing the fishery to a total standstill for a certain period of time, as it would require that fleets and manpower could be directed to some other use in the meantime, producing a value equal to the assumed opportunity cost. On the contrary, an optimal planning of the recovery would probably require a phased reduction of fishing effort.

The benefits dissipated by excessive fishing--to the extent that our assumption regarding fishing costs is realistic--are indicated by the difference between the present value of profits resulting, on the one hand, from maintaining the "recent" rate of exploitation, and, on the other, the optimal stationary rate. The extent of excessive fleet capacity is likewise indicated by the difference between the two fishing mortality rates, as fishing effort is assumed to be linearly related to fishing mortality. The importance of time preference as a determinant of optimal fishing effort--for the assumed cost of fishing--can be seen by comparing the optimal fishing mortality to that which maximizes stationary rent, which is optimal in the absence

of discounting. The two are not very far apart for the cost figures we have found reasonable to assume and the difference in terms of present value of profits is small, but for very low cost of fishing effort discounting even at 10% will in some cases tilt the optimum fishing mortality far beyond the level which corresponds to maximum sustainable yield, as will be shown below.

In contrast to case I, cases II and III represent attempts to reconcile the recent rate of exploitation and the maximization of the present value of profits. Case II shows how low the cost per unit of effort would have to be in order that this would obtain. Case III shows the same thing, with the discount rate being raised to 20% per year, which must be regarded as an upper limit or even beyond; the social rate of return on a marginal investment project would not be expected to be greater than that. The difference between the cost of fishing effort calculated under cases II and III and the figure assumed under case I indicates the likelihood of economic overfishing. As it is unlikely that any economic rents accrue to the fisheries in the worst years, i.e. those with the lowest catches per unit of effort, any difference between the cost figures under cases I and II or I and III would indicate economic overfishing, with the likelihood of overfishing increasing with this difference. The results will be presented below stock by stock.

4.7. The Economic Overfishing of the North Atlantic Cod

4.7.1. The Faeroe Islands Stock

This stock is really an amalgamation of two small stocks off the Faeroe Islands, considered in Clayden's report only. The mortality estimates obtained from age composition analysis show only total mortality (Z), from which the fishing mortality component must be separated. As is the case with most other stocks considered, linear regression of Z on fishing effort was insignificant and therefore of no help when it comes to separating the two mortality components ($Z = F + M$). As we know only Z in the relation $Z = F + M$, the estimation of F will depend on what assumption is being made about the natural mortality component. A natural mortality of 0.2 is assumed for all stocks, both by Clayden and the working group, but as high natural mortality means less overexploitation we shall also examine the implications of a natural mortality of 0.3, although it leads to a less satisfactory simulation of past catches. The results are summarized in Tables 4.2 and 4.3.

We have assumed a cost per unit of fishing effort equal to 0.25 TMT as a reasonable figure; this leaves only one year in the period 1960--1968 with a lower catch per unit of effort (cf. Table 4.1). With instantaneous natural mortality assumed equal to 0.2, the recent rate of exploitation clearly is

Table 4.2

		M = 0.2			
	F	cost per unit of effort	discount rate	present value of moratorium profits (years)	
Case I: recent exploitation	0.6	0.25 TMT	10%	63.755 TMT	-
max. sust. rent	0.21	0.25 TMT	10%	176.033 TMT	2
max. p.v. profits	0.27	0.25 TMT	10%	179.082 TMT	3
Case II: recent exploitation	0.6	0	10%	283.755 TMT	-
max. p.v. profits	0.53	0	10%	285.795 TMT	1
Case III: max. p.v. profits	0.6	0.0225 TMT	20%	143.976 TMT	-

Maximum sust. yield 27.95 TMT, average yield 1960--1968 27.72 TMT,
 $q=0.0075$, $R=20$ million, $F(\text{max. sust. yield})=0.45$.

Table 4.3

		M = 0.3			
	F	cost per unit of effort	discount rate	present value of moratorium profits (years)	
Case I: recent exploitation	0.5	0.25 TMT	10%	137.030 TMT	-
max. sust. rent	0.24	0.25 TMT	10%	192.829 TMT	1
max. p.v. profits	0.29	0.25 TMT	10%	194.882 TMT	2
Case II: max. p.v. profits	0.5	0.05 TMT	10%	313.030 TMT	-
Case III: max. p.v. profits	0.5	0.09375 TMT	20%	149.744 TMT	-

Maximum sust. yield 32.0 TMT, average yield 1960--1968 27.72 TMT,
 $q=0.00625$, $R=35$ million, $F(\text{max. sust. yield})=0.49$.

far beyond what is needed to maximize stationary rent and even sustainable yield (Table 4.2). Taking explicit account of time preference, setting the rate of discount at 10% per year, does indeed increase the optimal rate of exploitation, but the difference between maximizing the present value of profits and maximizing stationary annual profit--allowing a moratorium for recovery--is small, both in terms of fishing mortality and in terms of the present value of profits. It may seem odd that the optimal moratorium is longer when time preference is allowed to influence the rate of exploitation, but this of course in no way contradicts the fact that discounting indicates less willingness to wait for future benefits. The reason for this is that given discounting and given that fishing mortality were to be fixed at the suboptimal level that maximizes stationary annual profit, it would not be profitable to wait more than two years to resume the fishery.

Given a cost per unit of effort which would allow some economic rent to

accrue to the fishery in normal years, discounting at 10% would not suffice to make the recent rate of exploitation compatible with maximizing the present value of profits. Case II shows that it would in fact not be enough to lower the cost of fishing effort to zero, as the optimal rate of exploitation still falls short of its recent level. According to case III it would be necessary to assume a discount rate of 20% and negligible cost of fishing effort in order to conclude that the recent rate of exploitation had been compatible with maximizing the present value of profits.

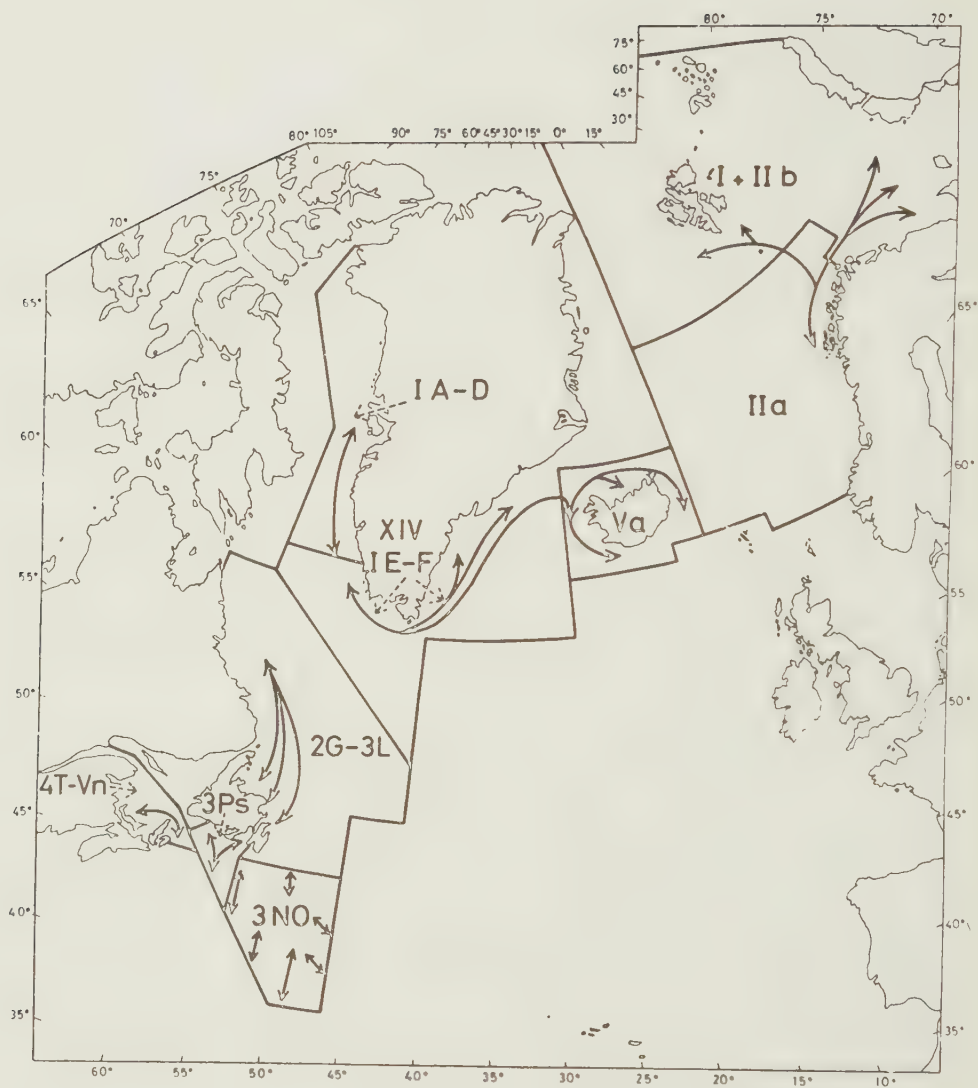
The alternative, and less reasonable, assumption about natural mortality (Table 4.3) alters the picture only slightly. While it is true that a high natural mortality rate does lessen the divergence between the recent and optimal rate of exploitation, because it implies less actual fishing mortality as well as a higher optimal rate of exploitation, it is not enough. Cases II and III show that it would be necessary to assume a rather low cost of fishing effort, implying that 60--80% of the catches in bad years constituted economic rent.

The conclusion therefore is that there is every indication of economically excessive exploitation of this stock, and that the annual economic rents collected by the fishery which exploits it could be increased in the long run by perhaps as much as twice their recent value by decreasing fishing effort to less than half its recent level.

4.7.2. The Stock at Iceland

The two reports differ with respect to the definition of this stock (area Va, cf. Fig. 4.9). A part of the catches taken by the Icelandic seasonal fishery concentrating on the spawning runs of the fish and for which no data on effort were obtained consists of fish originating from East Greenland; in some years this proportion has been estimated as high as 25%. Owing to this difficulty to distinguish between the stocks at Iceland and East Greenland, Clayden chose to ignore the Icelandic seasonal fishery altogether and consider only that part of the stock which is exploited by international fleets on an all year round basis. We shall consider Clayden's data first; the results are shown in Tables 4.4 and 4.5.

The conclusions that emerge from simulating this fishery are very similar to the ones that were presented above for the stock at the Faeroe Islands. Our assumption of a cost per unit of effort at 0.55 TMT leaves one year with a slightly lower catch per unit of effort and some economic rent in other years (cf. Table 4.1). For natural mortality equal to 0.2, it is necessary to lower the cost of effort to less than one fifth of its "reasonable" level and discount at 20% in order to find the recent level of exploitation compatible



Main North Atlantic Cod Stocks and their Migrations.

Fig. 4.9

Table 4.4

M = 0.2

	F	cost per unit of effort	discount rate	present value of moratorium profits (years)
Case I: recent exploitation	0.57	0.55 TMT	10%	485.289 TMT -
max. sust. rent	0.21	0.55 TMT	10%	1279.971 TMT 2
max. p.v. profits	0.25	0.55 TMT	10%	1303.195 TMT 3
Case II: recent exploitation	0.57	0	10%	2052.789 TMT -
max. p.v. profits	0.50	0	10%	2069.082 TMT 1
Case III: max. p.v. profits	0.57	0.044 TMT	20%	1051.303 TMT -

Maximum sust. yield 200 TMT, average yield 1960--1968 155 TMT,
 $q=0.0022$, $R=200$ million, $F(\text{max. sust. yield})=0.33$

Table 4.5

M = 0.3

	F	cost per unit of effort	discount rate	present value of moratorium profits (years)
Case I: recent exploitation	0.47	0.55 TMT	10%	680.068 TMT -
max. sust. rent	0.22	0.55 TMT	10%	1144.220 TMT 2
max. p.v. profits	0.25	0.55 TMT	10%	1154.614 TMT 3
Case II: max. p.v. profits	0.47	0.1044 TMT	10%	2003.588 TMT -
Case III: max. p.v. profits	0.47	0.1914 TMT	20%	951.866 TMT -

Maximum sust. yield 210 TMT, average yield 1960--1968 155 TMT,
 $q=0.00174$, $R=360$ million, $F(\text{max. sust. yield})=0.46$.

with maximizing the present value of profits (Table 4.4). A natural mortality of 0.3 still implies that more than a half of the catch per unit of effort in worse than normal years would have contributed to economic rent. Fishing effort appears to be too large in both cases, or about twice its optimal size; decreasing fishing effort to the optimal level would increase profits by 75--170%, according to the calculations.

One difference between this fishery and the one off the Faeroe Islands is that a simulation with a natural mortality at 0.3 reproduces the past pattern of catches slightly better than the alternative assumption of 0.2. This may reflect the fact that the Icelandic seasonal fishery also exploits this stock, which means additional mortality of older fish. The result emerging from the higher assumption about natural mortality (Table 4.5) may therefore be interpreted in the following way: Let us regard the exploitation of this stock as being conducted by two distinct parts, the Icelanders and the

English, who are predominant in the international fishery. A one-sided reduction of English fishing effort with Icelandic effort remaining unchanged would always leave more fish to be caught by the Icelanders, but, as case I shows, would benefit the English themselves substantially as well. Only if the discount rate is higher than 20%, as assumed in case III, would such an action be futile. A high discounting of future profits may perhaps be expected in this case, given the prospect of extension of the Icelandic fishing limits.

A major difference between the approach followed by Clayden and the working group with respect to this stock is that the working group attempted to include the seasonal fishery for spawning cod. Thus it identified two different fisheries having quite different selectivity patterns with this stock. An attempt to optimize the exploitation immediately raises the question of the optimal proportion between the two fisheries, which we know from the preceding discussion of the Beverton-Holt model to be dependent on the cost of effort in each fishery, as the optimal pattern of selectivity depends on cost. We shall, however, avoid becoming involved with this aspect and proceed as if the proportion of fishing effort in the two fisheries will be maintained for any reduction in fishing effort. This approach is not so unsatisfactory as it may appear, as there are quite different interests behind each fishery as already explained. Much the same applies to the Arcto-Norwegian stock, with the fishery off the Norwegian coast being heavily dominated by Norwegian vessels with a limited range of action, concentrating on the seasonal spawning run. Our comments here on a mixed fishery apply equally to the Arcto-Norwegian stock, and will not be repeated. It must be noted, however, that preserving each fishery's proportion of total fishing effort is not the same as preserving the proportion of the total catch taken by each fishery, since that fishery which concentrates on the older part of the fish population will benefit most from a reduction of fishing effort. This question would of course have to be considered if a reduction of fishing effort had become an objective of management, but we need not get involved with it here in order to conclude whether or not the overall rate of exploitation is too high from an economic point of view.

The assumption of a constant share of each fishery in total effort makes it possible to arrive at a selectivity pattern for the aggregate fishery which is independent of total fishing effort:

$$(4.14) \quad \bar{\epsilon}_h = \frac{\epsilon_h^1 \cdot q^1 \cdot \bar{f}^1 + \epsilon_h^2 \cdot q^2 \cdot \bar{f}^2}{q^1 \cdot \bar{f}^1 + q^2 \cdot \bar{f}^2}$$

where h denotes age and the superscripts denote fishery "one" and "two" respectively, with $\bar{f}$ being average fishing effort 1960--1968.

As explained in the Appendix, the average fishing effort in the Icelandic seasonal fishery was calculated by assuming an average catch per unit of effort of 0.6 TMT. Assuming the cost per unit of effort equal to 0.55 TMT as in the international fishery would therefore leave room for some economic rent under average conditions. An instantaneous natural mortality of 0.3 leaves too little fish to be caught by the seasonal fishery and was therefore not considered.

Our simulations (Table 4.6) show a complete dissipation of rents and recent fishing effort exceeding the optimum level, although less than required to take the maximum sustainable yield, owing to the peculiar shape of the yield curve produced by the pattern of selectivity in the aggregate fishery. (Note the high maximum sustainable yield fishing mortality, 2.57.) The cost of fishing effort would have to be quite low in order to conclude that the "recent" level of effort had in fact been optimal, or about 35% of what we considered reasonable, with the discount rate as high as 20%, but lower still otherwise. The moratorium figures indicate overexploitation already before 1960.

TABLE 4.6

	F	cost per unit of effort	discount rate	present value of profits	present value of moratorium profits (years)
Case I: recent exploitation	0.9	0.55 TMT	10%	-897.813 TMT	-
max. sust. rent	0.26	0.55 TMT	10%	1181.739 TMT	2
max. p.v. profits	0.29	0.55 TMT	10%	1190.881 TMT	2
Case II: max. p.v. profits	0.9	0.14887 TMT	10%	3241.961 TMT	-
Case III: max. p.v. profits	0.9	0.18948 TMT	20%	1655.163 TMT	-

Maximum sustained yield 407 TMT, average yield 1960--1968 391 TMT,
 $q_1=0.0005$, $q_2=0.0014$, $R=200$ million, $F(\text{max, sust, yield})=2.57$

Again, it should be emphasized that the exact value of optimal fishing mortality as well as the resulting present value of profits depend critically on the assumption of a constant proportion of effort in both fisheries. The seasonal fishery which concentrates on older fish appears to be too predominant, as the aggregate selectivity obviously is inoptimal, allowing the fish to attain too high an age on the average, and all the more so the higher is the cost of fishing effort. On the other hand, if there is a cost differential in favour of the seasonal fishery, it would turn the optimal balance in its favour, provided we ignore the question to whom the benefits accrue (cf. Chapter 5). It is possible, however, that the selectivity pattern of the Icelandic seasonal fishery is in reality less heavily biased toward older age groups than indicated by the working group's data, as spawning fish of East

Greenland origin might have been in the sample from which selectivity was estimated. This would of course have the effect that too large a proportion of the catches taken by this fishery consists of "old" fish. But what both Clayden's and the working group's data seem to imply beyond any reasonable doubt is that this stock is heavily overexploited from an economic point of view.

4.7.3. The Arcto-Norwegian Stock

The Barents Sea and Bear Island areas (I and IIb, cf. Fig. 4.9) are inhabited by the Arcto-Norwegian stock, the mature part of which migrates to the Northwest coast of Norway to spawn (area IIa). It is possible to identify two or three distinct fisheries that exploit this stock, one of which concentrates on the spawning run of mature fish off the Norwegian coast. Clayden distinguishes between the stocks in the Barents Sea and off Bear Island, whereas the working group does not, but the main difference between the two is that the gear selectivity parameter (ϵ_h) exceeds 1 for some age groups according to the working group, in order to reflect their migration more adequately (cf. Fig. 4.10). A natural mortality of 0.3 leaves too little fish to be caught by the fishery off the Norway coast and was not further considered.

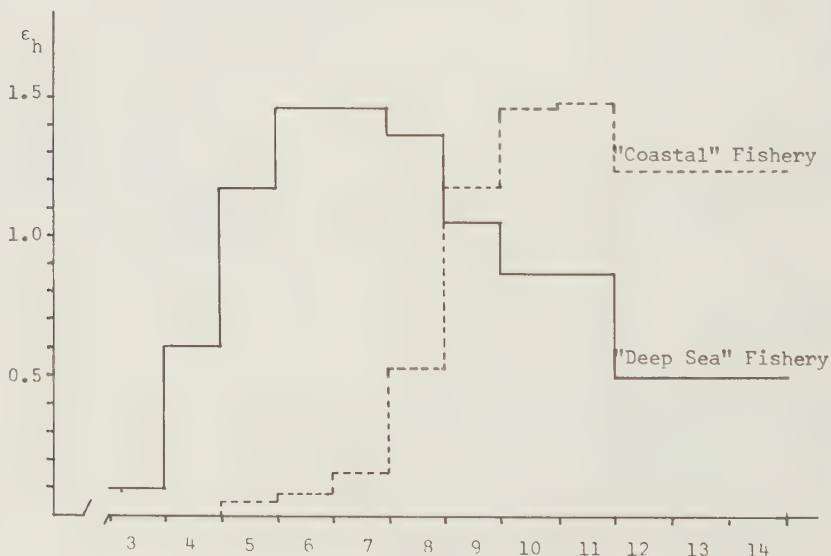


Fig. 4.10

As we shall not consider the optimal proportion of the fisheries connected with each stock,¹ it is not of any great importance to discuss the cost of fishing effort with regard to each fishery separately. It seems reasonable to make the following assumptions with regard to the cost per unit of fishing effort: For the Barents Sea stock a cost of 0.55 TMT per unit of effort is lower than any catch per unit of effort figure for the English fleet in that area 1960--1968, and leaves only one year with a lower figure for the fishery off the Norwegian coast (Table 4.1). As the catches per unit of effort in the Bear Island area are consistently larger, we assume a cost per unit of effort at 0.7 TMT for this stock. When considering the Arcto-Norwegian stock as one unit like the working group did, we assume a cost per unit of effort equal to 0.6 TMT, as the Barents Sea fishery is roughly twice as large as the other. The results are presented in Tables 4.7 and 4.8 (Clayden's data), and 4.9 (working group's data).

As was the case with the stock at Iceland, Clayden and the working group differ considerably with regard to the estimates of biological parameters such as weight at age, and, particularly, the selectivity parameters of the various fisheries. As an example, the fishing mortality which would suffice for maximum sustained catch is much higher according to Clayden's figures than those presented by the working group, despite the fact that we have assumed the same proportion between the two fisheries in both cases. The reason is that the selectivity pattern estimated by the working group directs a larger proportion of the overall fishing mortality towards young age groups. Both however lead to the conclusion that the Arcto-Norwegian stock has been excessively exploited. Clayden's figures indicate a greater overfishing (Tables 4.7 and 4.8) which is to be expected, as they refer to an earlier period and fishing effort diminished in this area towards the end of the 1960s. According to his figures, it would be necessary to assume a costless fishing with a discount rate of 10% in order to find the recent rate of exploitation compatible with a maximization of the present value of profits. Raising the discount rate to 20% does not greatly affect this conclusion; it would in that case be necessary to assume an extremely low cost per unit of fishing effort, which would imply that 80% (Barents Sea) or 90% (Bear Island) of the catches per unit of effort in "bad" years constituted economic rent, in order to find the recent rate of exploitation compatible with maximizing the present value of profits.

The results that emerge from using the working group's data are similar.

1 Cf. the discussion of the two fisheries at Iceland.

Table 4.7

	Barents Sea (Clayden)			present value of moratorium profits (years)	
	F	cost per unit of effort	discount rate		
Case I: recent exploitation	0.9	0.55 TMT	10%	1452.493 TMT	-
max. sust. rent	0.34	0.55 TMT	10%	2969.582 TMT	2
max. p.v. profits	0.44	0.55 TMT	10%	3009.000 TMT	3
Case II: max. p.v. profits	0.9	0	10%	4851.530 TMT	-
Case III: max. p.v. profits	0.9	0.1121 TMT	20%	2268.289 TMT	-

Maximum sustained yield 465 TMT, average yield 1960--1968 486 TMT,
 $q_1=0.001$, $q_2=0.003$, $R=655$ million, $F(\text{max. sust. yield})=0.54$.

Table 4.8

	Bear Island (Clayden)			present value of moratorium profits (years)	
	F	cost per unit of effort	discount rate		
Case I: recent exploitation	1.05	0.7 TMT	10%	-699.578 TMT	-
max. sust. rent	0.28	0.7 TMT	10%	833.626 TMT	3
max. p.v. profits	0.32	0.7 TMT	10%	841.899 TMT	3
Case II: max. p.v. profits	1.05	0	10%	1819.547 TMT	-
Case III: max. p.v. profits	1.05	0.0642 TMT	20%	866.480 TMT	-

Maximum sustained yield 176 TMT, average yield 1960--1968 195 TMT,
 $q_1=0.0035$, $q_2=0.003$, $R=240$ million, $F(\text{max. sust. yield})=0.58$.

Table 4.9

	(Working group)			present value of moratorium profits (years)	
	F	cost per unit of effort	discount rate		
Case I: recent exploitation	0.6	0.6 TMT	10%	3239.743 TMT	-
max sust. rent	0.23	0.6 TMT	10%	6016.236 TMT	3
max. p.v. profits	0.28	0.6 TMT	10%	6119.795 TMT	-
Case II: recent exploitation	0.6	0	10%	9141.439 TMT	-
max. p.v. profits	0.55	0	10%	9148.462 TMT	0
Case III: max. p.v. profits	0.6	0.1 TMT	20%	4312.132 TMT	-

Maximum sustained yield 878 TMT, average yield 1960--1968 835 TMT,
 $q_1=0.0005$, $q_2=0.0012$, $R=900$ million, $F(\text{max. sust. yield})=0.33$.

The moratorium figures are as high or even higher than the ones produced by Clayden's data, which indicates serious overexploitation already before 1960. Even with a discount rate as high as 20% it would still be necessary to assume an unreasonably low cost per unit of fishing effort in order to find that the recent level of exploitation had maximized the present value of profits. Both sets of data indicate that fishing effort should be reduced to less than half its recent level in order to maximize the present value of profits, but Clayden's figures produce a rather greater benefit from reducing fishing effort.

As with respect to the Iceland cod, a proportional reduction of fishing effort in both the "spawning" fishery and the other one that concentrates more on the younger cohorts would benefit the "spawning" fishery more. It is very possible, not to say probable, that the proportion of the fishery off the Norwegian coast should be increased. Again, that is a separate question raising the issues of comparative costs and the distribution of benefits and does not of itself thwart the conclusion of overfishing.

4.7.4. The Stocks at Greenland

Clayden distinguishes between three stocks at Greenland, East (area XIV), Southwest (area 1E--F) and Northwest (area 1A--D), whereas the working group does not distinguish between the stocks at East and Southwest Greenland. While Clayden uses different growth parameters for each stock, the wage at age figures in the report of the working group are identical for both stocks considered. We have therefore treated the Greenland cod as one stock when using the data provided by the working group, simply adding the figures for annual recruitment and the size of the initial age groups. The selectivity patterns are not very different; for simplicity we assumed the selectivity of the aggregate fishery to be the average of the two.

The catches per unit of effort are higher in these waters, being far from the main fishing and marketing ports of Western Europe, and also more variable than in the eastern stocks that we have considered above. We have assumed a cost per unit of effort equal to 0.6 TMT at East Greenland, but 1 TMT in the other areas. This is lower than any recorded catch per unit of effort 1960--1968, except one year at Northwest Greenland (cf. Table 4.1). When using the working group's data the cost per unit of effort was set at 1 TMT, as the fishery at East Greenland is a very small part of the total. The results of simulating the fisheries are shown in Tables 4.10--4.13.

The conclusions emerging from the two sets of data are quite different. According to Clayden's figures, no stock at Greenland was exploited beyond maximum sustainable yield level in the first half of the 1960s. Nevertheless, his figures indicate some economic overexploitation, as the present value of

Table 4.10

	East Greenland (Clayden)			present	
	F	cost per unit of effort	discount rate	value of moratorium profits (years)	
Case I: recent exploitation	0.35	0.6 TMT	10%	50.140 TMT	-
max. sust. rent	0.21	0.6 TMT	10%	65.281 TMT	1
max. p.v. profits	0.23	0.6 TMT	10%	65.499 TMT	1
Case II: max. p.v. profits	0.35	0.3375 TMT	10%	117.515 TMT	-
Case III: max. p.v. profits	0.35	0.39 TMT	20%	56.749 TMT	-

Maximum sustained yield 22 TMT, average yield 1960--1968 21 TMT,
 $q=0.015$, $R=22$ million, $F(\text{max. sust. yield})=1.37$

Table 4.11

	Southwest Greenland (Clayden)			present	
	F	cost per unit of effort	discount rate	value of moratorium profits (years)	
Case I: recent exploitation	0.35	1.0 TMT	10%	310.535 TMT	-
max. sust. rent	0.23	1.0 TMT	10%	341.894 TMT	1
max. p.v. profits	0.26	1.0 TMT	10%	344.017 TMT	1
Case II: max. p.v. profits	0.35	0.5 TMT	10%	503.035 TMT	-
Case III: max. p.v. profits	0.35	0.65 TMT	20%	242.883 TMT	-

Maximum sustained yield 65 TMT, average yield 1960--1968 77 TMT,
 $q=0.01$, $R=100$ million, $F(\text{max. sust. yield})=0.54$

Table 4.12

	Northwest Greenland (Clayden)			present	
	F	cost per unit of effort	discount rate	value of moratorium profits (years)	
Case I: recent exploitation	0.35	1.0 TMT	10%	1297.227 TMT	-
max. sust. rent	0.23	1.0 TMT	10%	1391.909 TMT	1
max. p.v. profits	0.26	1.0 TMT	10%	1405.047 TMT	1
Case II: max. p.v. profits	0.35	0.575 TMT	10%	1951.727 TMT	-
Case III: max. p.v. profits	0.35	0.75 TMT	20%	917.579 TMT	-

Maximum sustained yield 272 TMT, average yield 1960--1968 292 TMT,
 $q=0.0025$, $R=275$ million, $F(\text{max. sust. yield})=0.65$.

Table 4.13

	(working group)			present	
	F	cost per unit of effort	discount rate	value of profits	moratorium (years)
Case I: recent exploitation	0.6	1.0 TMT	10%	-930.906 TMT	-
max. sust. rent	0.12	1.0 TMT	10%	667.082 TMT	0
max. p.v. profits	0.16	1.0 TMT	10%	704.825 TMT	0
Case II: max. p.v. profits	0.6	0.136 TMT	10%	2421.894 TMT	-
Case III: max. p.v. profits	0.6	0.289 TMT	20%	1432.570 TMT	-

Maximum sustained yield 165 TMT, average yield 1960--1968 325 TMT,
 $q=0.0017$, $R=120$ million, $F(\text{max. sust. yield})=0.6$

profits can be increased in all areas by reducing fishing effort, albeit not very much, and "recent" fishing effort does not exceed the optimum level as grossly as in the eastern areas considered above. Much less extreme assumptions about the cost of fishing effort are needed to reconcile the recent rate of exploitation with a maximization of the present value of profits.

The moratorium figures arrived at on the basis of the working group's data also indicate that the stocks at Greenland were not overexploited prior to 1960, but apart from that, the conclusions to be drawn from the working group's data are different. According to Table 4.13 recent level of exploitation maximized sustainable yield, with rents being completely dissipated. To conclude that this rate of exploitation was not excessive would require almost as extreme assumptions about the cost of effort as with respect to the eastern areas (cf. cases II and III Table 4.13).

The difference between the results obtained from the two reports reflects the fact that fishing effort increased very substantially in this area towards the end of the 1960s. The "recent" rate of exploitation when simulating the working group's model refers to a later period than the case is for Clayden's model (cf. *supra*); it seems therefore beyond dispute that the stocks at Greenland became overexploited towards the end of the 1960s, provided that rate of exploitation were to be maintained.

Two more remarks are in order: First, a comparison of the maximum sustained yield in Table 4.13 (bottom) and the average yield 1960--1968 indicates that the working group underestimated average recruitment to this stock; this is supported also by comparing its recruitment figure to those arrived at by Clayden. As the working group's figure shows expected recruitment 1970 and beyond on the basis of whatever evidence it had at the time of its investigation, it reflects the extremely unfavourable conditions for recruitment of

young codfish in this area after 1969. Too low recruitment displaces the yield curve downwards, without however affecting the fishing mortality required for taking maximum sustainable yield, but would lower the optimum fishing mortality provided it does not exceed that level (cf. the discussion in Section 4.5). Secondly, a higher natural mortality than 0.2 which has been assumed here, would imply less excessive fishing effort (cf. the discussion in Sections 4.5, 4.7.1 and 4.7.2).

4.7.5. The Stocks at Labrador/Newfoundland and on the Grand Bank

Clayden's and the working group's definition of these stocks differ from one another, so that the results are not quite comparable. The working group identifies the Labrador/Newfoundland stock with area 2G--3L, while Clayden identifies area 3L with the Grand Bank stock, which by the working group is limited to areas 3N--0 (cf. Fig. 4.9). Assuming a cost per unit of effort of 1.0 TMT appears to be cautious according to Table 4.1.

The results for the Labrador/Newfoundland stock (Tables 4.14 and 4.15) are very similar to the ones obtained for the stocks at Greenland. The results obtained on the basis of Clayden's figures indicate only slight economic overexploitation, and a discount rate of 20% is almost enough to reconcile the recent rate of exploitation with a maximization of the present value of profits. The working group's figures on the other hand give rise to results that show complete dissipation of rents, and extreme assumptions about the cost of fishing effort are needed in order to make the recent rate of exploitation compatible with a maximization of the present value of profits. The conclusion therefore is that the high rate of exploitation of this stock, like those at Greenland, that resulted from the rapid expansion of fishing effort

Table 4.14

	Labrador/Newfoundland (Clayden)			present	
	F	cost per unit of effort	discount rate	value of profits	moratorium (years)
Case I: recent exploitation	0.25	1.0 TMT	10%	991,258 TMT	-
max. sust. rent	0.19	1.0 TMT	10%	1049,792 TMT	1
max. p.v. profits	0.21	1.0 TMT	10%	1051,410 TMT	1
Case II: max. p.v. profits	0.25	0.697 TMT	10%	1480,758 TMT	-
Case III: max. p.v. profits	0.25	0.833 TMT	20%	687,686 TMT	-

Maximum sustained yield 268 TMT, average yield 1960--1968 399 TMT,
 $q=0.0017$, $R=700$ million, $F(\text{max. sust. yield})=0.55$

Table 4.15

	Labrador/Newfoundland (working group)			present value of moratorium profits (years)	
	F	cost per unit of effort	discount rate		
Case I: recent exploitation	0.6	1.0 TMT	10%	-183.845 TMT	-
max. sust. rent	0.20	1.0 TMT	10%	3070.488 TMT	0
max. p.v. profits	0.21	1.0 TMT	10%	3070.732 TMT	0
Case II: max. p.v. profits	0.6	0.12 TMT	10%	7076.155 TMT	-
Case III: max. p.v. profits	0.6	0.24 TMT	20%	3491.272 TMT	-

Maximum sustained yield 714 TMT, average yield 1960--1968 710 TMT,
 $q=0.0008$, $R=1160$ million, $F(\text{max. sust. yield})=0.5$

in the latter half of the 1960s implies economic overexploitation if maintained. The moratorium figures calculated in Table 4.15 also indicate that this stock was not overexploited prior to 1960.

The results with respect to the Grand Bank stock are more similar to the eastern stocks that are close to the main fishing ports and markets of Western Europe. The Grand Bank is more easily accessible to European fishermen and fishing is less hampered by ice and bad weather than the case is for the more distant stocks at Labrador/Newfoundland and at Greenland. Even the results obtained from Clayden's figures indicate economic overexploitation (Table 4.16), otherwise more than half of the catches per unit of effort in bad years would have constituted profits in excess of opportunity cost. The results derived from the working group's figures show a still greater overexploitation; an assumption of zero fishing costs would be needed to find that the recent rate of exploitation accorded with a maximization of the present value of profits,

Table 4.16

	Grand Bank (Clayden)			present value of moratorium profits (years)	
	F	cost per unit of effort	discount rate		
Case I: recent exploitation	0.3	1.0 TMT	10%	782.536 TMT	-
max. sust. rent	0.16	1.0 TMT	10%	1163.749 TMT	2
max. p.v. profits	0.18	1.0 TMT	10%	1176.737 TMT	2
Case II: max. p.v. profits	0.3	0.306 TMT	10%	2128.936 TMT	-
Case III: max. p.v. profits	0.3	0.476 TMT	20%	981.238 TMT	-

Maximum sustained yield 248 TMT, average yield 1960--1968 307 TMT,
 $q=0.0017$, $R=600$ million, $F(\text{max. sust. yield})=0.34$.

with the discount rate at 10%. Discounting at 20% would still make it necessary to assume an extremely low cost per unit of effort. The moratorium figures in Table 4.17 indicate overexploitation already prior to 1960.

Table 4.17

	Grand Bank (working group)			present	value of moratorium
	F	cost per unit of effort	discount rate	profits	(years)
Case I: recent exploitation	0.4	1.0 TMT	10%	90.182 TMT	-
max. sust. rent	0.15	1.0 TMT	10%	558.875 TMT	3
max. p.v. profits	0.18	1.0 TMT	10%	566.979 TMT	3
Case II: max. p.v. profits	0.4	0	10%	1190.182 TMT	-
Case III: max. p.v. profits	0.4	0.2 TMT	20%	548.084 TMT	-

Maximum sustained yield 111 TMT, average yield 1960--1968 142 TMT,
 $q=0.004$, $R=100$ million, $F(\text{max. sust. yield})=0.27$

4.8. Summary

Our analysis of the major North Atlantic cod fisheries has indicated excessive exploitation from an economic point of view, as predicted by the theory of exploiting a common property resource. While it has been established that the optimal rate of exploitation is a function of the discount rate, its impact does not appear to be very great; a 10% annual rate of discount does not tilt the optimum fishing mortality beyond that which maximizes sustainable yield for any assumption about the cost of fishing effort that appears to be reasonable. No reasonable combination of "low" fishing cost and "high" discount rate is capable of explaining the recent history of these fisheries as being compatible with an intertemporal maximization of rents. On the contrary there seem to have been considerable benefits to be acquired by restricting fishing effort in this area in the past, particularly in the eastern part where overexploitation occurred already prior to 1960.

The assumptions of bionomic equilibrium and a constant relative price of fish are shortcomings of our approach that it is necessary to acknowledge. The assumption of a constant relative price of fish is in our judgement the least serious one. As long as we are interested in long term prospects under average conditions this assumption would have to be rejected only if the relative price of fish was likely to change in future; e.g. rise in response to an increase in income for less well off groups or increase in population, or else if a more rapid technological progress was expected to occur in fisheries than in other industries. It is to be noted that the impact of such changes

on the optimal time-pattern of fishing is limited, since they would take place gradually, and the short life-span of fish sets definite limits to how long it would be profitable to defer the harvest of a given stock of fish. A more valid objection is that we might be asking the wrong question, as the short term variations in the rate of exploitation would be the most relevant problem to consider. This is where the assumption of bionomic equilibrium becomes awkward, as it presupposes a constant recruitment of young fish, or else a stable recruitment function, neither of which is the case. We have already mentioned the large, stochastic fluctuations in recruitment that characterize the cod stocks, and one would therefore expect that the optimal fishing strategy would involve an uneven rate of exploitation and some rotation of fleets between areas. We shall address ourselves to this problem in the next chapter, but it may be stated here that optimal rotation of fleets between areas would not invalidate the conclusion that the area as a whole has been excessively exploited in the past.

There are important differences between Clayden's and the working group's investigations with respect to the measurement of effort and the estimation of the availability coefficient. The working group measures fishing effort in English fishing hours, unadjusted for vessel size. Since average vessel size varies from one area to another and fishing power is related to vessel size, the working group's data on fishing effort in any two areas are not directly comparable. Secondly, the availability coefficient varies from one year to another in the working group's report, besides fluctuating seasonally as mentioned in Chapter 4. This does not, however, contradict our argument that the availability coefficient may reasonably be assumed to be constant in the sense of a repetitive pattern year after year, as the year-to-year fluctuations shown in the report of the working group are apparently stochastic.¹

As we are interested in long term average conditions, it is necessary to estimate the average annual availability coefficient from the data in the working group's report. Since the availability coefficient varies with the unit of measurement of fishing effort (cf. Eq. 4.5) and since in Chapter 5 we shall be interested in measuring effort in identical units in all areas, we attempted to estimate the average annual availability coefficient using Clayden's standardized data on effort whenever compatible with the identification of fish stocks in the two reports. This is not possible with respect to the Grand Bank and the Labrador/Newfoundland areas, and the figures provided by the working group were therefore converted to ton-hours by multiplying its estimates of annual fishing effort by average vessel size. On the basis of Table A 4.1 we assumed the average vessel size to be 900 Grt. on the Grand Bank and 1000 Grt. off Labrador/Newfoundland.

Table A 4.1

Percentage distribution of catches in 1970 by vessel categories

Stock:	500 GRT	501--900 GRT	901 + GRT
Labrad./Newf.	18	18	64
Grand Bank	7	61	32

Source: Anon. 1972.

¹ There is one stock in the working group's report where the availability coefficient has increased with increasing fishing effort and decreasing biomass, i.e. the Greenland stock. The theory is advanced that this has to do with the introduction of more efficient gear (midwater trawl) and a greater concentration of fishing in the season when the availability is highest. (Anon. 1972, pp. 5). However, it is the opinion of Dr. Garrod that the availability coefficient may very possibly be a decreasing function of stock size (personal communication).

Since the working group's figures are inflated by 3% per year with 1960 as a base in order to account for "increase in efficiency", it would imply that average vessel size had increased to 1343.9 and 1209.5 Grt. in 1970, if the increase in efficiency is due to--or manifests itself as--an increase in vessel size. This is rather too high according to Table A 4.1, but on the other hand it seems to be roughly consistent with Clayden's estimates of fishing effort. From Table 4.1 it may be calculated that the average catch per unit of effort in those two areas was 1.61 and 1.35 TMT respectively in the period 1960--1967 according to Clayden's estimates, compared to 1.68 and 1.33 TMT implied by our adjustment of the estimates of the working group. This is, however, of no importance for the discussion in Chapter 4 but will be more relevant in Chapter 5. Our conclusions in Chapter 4 rest on the probable cost per unit of fishing mortality (C), calculated from the following relation

$$(A\ 4.1) \quad C \approx \min \left(\frac{\text{catch}/f}{q} \right)$$

We have argued that the opportunity cost of fishing effort may be expected to be approximately equal to the lowest catch per unit of effort recorded in 1960--1968. As our estimation of q (the availability coefficient) involves finding the fishing mortality (F) which reproduces the past pattern of catches in the most satisfactory way, and, furthermore, because of the relationship $F = q \cdot f$, it follows that a consistent overestimate of fishing effort, such as would result from overestimating average vessel size, would only produce a lower q and vice versa, the success of the simulation of past catches depending only on the value of F . Therefore, we would always be considering the same $\min \left(\frac{\text{catch}/f}{q} \right)$, regardless of our estimate of fishing effort.

The absence of effort data from the Icelandic fishery has already been mentioned. For our purposes here we have assumed a constant annual effort of 400 MTH, calculated by setting the average catch per unit of effort equal to 0.6 TMT, which is about the same as in the international fishery off Iceland and the fishery off the Norway coast. This assumption is likewise unimportant for the discussion in Chapter 4, as by Eq. (A 4.1) a different assumption of annual effort would not affect $\min \left(\frac{\text{catch}/f}{q} \right)$.

The results of the simulation by which we estimated the availability coefficient are shown in Fig. A 4.1 - A 4.4; note that there are two distinct fisheries associated with the Arcto-Norwegian and the Iceland stocks. The apparently poor result with respect to the Icelandic fishery is due to the absence of adequate data on effort. The availability coefficients for the fisheries considered by Clayden were taken directly from his report, except for the Arcto-Norwegian stock, where his figures result in a rather poor simu-

lation of past catches and were replaced by our own estimates. Estimates of weight at age, recruitment and gear selectivity were taken from the two reports.

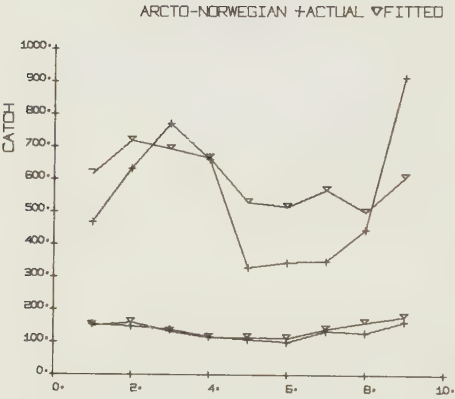


Fig. A 4.1

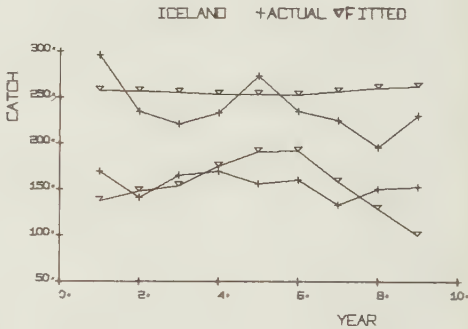


Fig. A 4.2

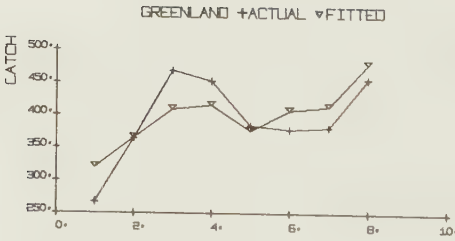


Fig. A 4.3

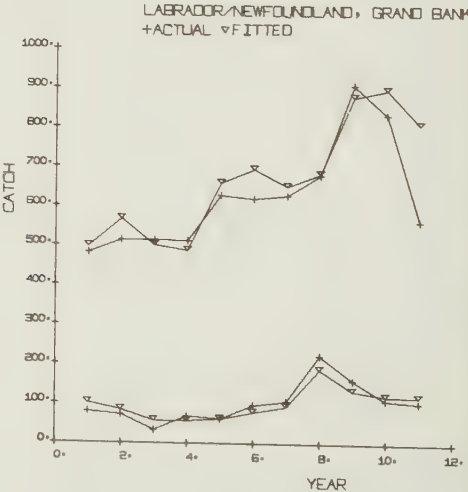


Fig. A4.4

Chapter 5

FISHERY DYNAMICS: PERIODIC OR SUSTAINED EXPLOITATION OF THE NORTH ATLANTIC COD?

5.1. Introduction

Up to now we have been concerned with stationary states. It has been assumed that the optimal rate of fishing is stationary, given a constant price of fish and cost per unit of fishing mortality together with technological and environmental conditions, but that need not be the case. In this chapter it will be shown that the optimal rate of fishing may in fact be variable under these circumstances.

Although a feasible stationary rate of exploitation by definition has the virtue of resulting in a sustainable yield, a variable rate of exploitation could also give a yield that is sustainable in the sense of a repetitive fishing cycle. A sufficiently high discount rate and a cost to catch the last fish that is lower than its price will however imply that extinction of the species is optimal, provided there is no "option demand" for preserving the species as such (cf. Clark, 1973a).

We shall begin (Section 5.2) by considering the harvesting of a single year class of fish, taking an approach similar to Clark *et al.* (1973.) Although this is not a very realistic case to consider, it is convenient for demonstrating the important role of the stock as a factor of production and not merely as a growing asset, given the "encounter" technology peculiar to fisheries. It will be shown that only in the special cases of no discounting or costless fishing would it be optimal to harvest at a maximum feasible rate until the biomass has been reduced to an unprofitable level, contrary to cases where the growing asset is fully under control and the cost of "harvesting" one unit is not dependent on the total size (or value) of the asset (forests, wine).

In the remaining sections we shall compare stationary and variable fishing in a Beverton-Holt model. The approach taken is to simulate the fishery for cod at Iceland. Similar approaches have been taken by Walters (1969) and Pope (1973), who were interested only in physical yield and did not consider the impact of costs or discounting. It will be shown that periodic fishing is superior to stationary fishing in the absence of perfectly controllable knife-edge selectivity of gear, even under circumstances that would otherwise be favourable for a stationary solution.

In Section 5.5 the practicability of periodic fishing is discussed in general terms, but in Section 5.6 we venture into a speculation on periodic fishing in the North Atlantic cod fisheries. In order to be feasible, periodic fishing of these stocks would in all probability require that a fishing

fleet of more or less constant size were rotated between the different stocks. We argue that the fishing technology required would be more costly than more traditional fleets harvesting each stock on a sustained basis. Such cost differential as appears to be consistent with recent data would be more than enough to destroy the profitability of periodic fishing.

5.2. Optimal Fishing of a Single Year Class

Suppose that each year class of fish is kept isolated from other year classes. The growth of each fish is described by a curve similar to the one in Fig. 4.1, and the resulting growth of the total biomass follows a curve like the one in Fig. 4.5, reproduced as locus β in Fig. 5.1. Estimates of the growth of individual fish of Iceland cod are shown in Table 5.1.

Retaining the assumption of a constant availability coefficient, fish price and cost per unit of effort, maximization of the present value of pro-

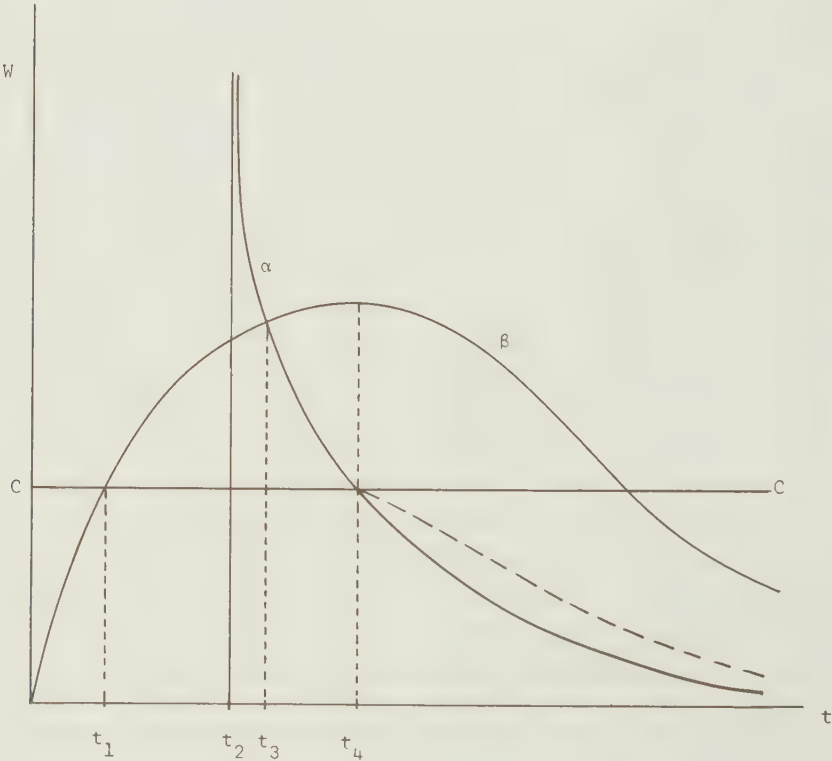


Fig. 5.1

Table 5.1

Age h	weight (kilograms) $\bar{w}_h$	Relative growth rate $\frac{\Delta \bar{w}}{\bar{w} + \frac{1}{2} \Delta \bar{w}}$	$\frac{\Delta \bar{w}}{\bar{w} + \frac{1}{2} \Delta \bar{w}} - M^a)$	Biomass at beginning of year in ab- sence of fishing $Re^{-M(t-t_r)} \bar{w}_{t-t_r}$
1	0.033	1.54	1.36	6.6
2	0.26	0.98	0.80	42.6
3	0.76	0.73	0.55	101.9
4	1.53	0.43	0.25	168.0
5	2.52	0.38	0.20	226.5
6	3.72	0.31	0.13	273.7
7	5.1	0.25	0.07	307.2
8	6.54	0.23	0.05	322.5
9	8.23	0.16	-0.02	332.3
10	9.66	0.15	-0.03	319.4
11	11.2	0.13	-0.05	303.2
12	12.8			283.7

a) M is here equal to 0.18, which is approximately equal to an instantaneous rate of 0.2.

fits from exploiting a year class of fish recruited at time t_r is equivalent to maximizing the integral

$$(5.1) \quad \int_{t_r}^{\infty} F \cdot (W-C) \cdot e^{-\rho t} dt \quad (\text{cf. Eq. 4.12})$$

where C is opportunity cost per unit of fishing mortality (c/q) and ρ denotes the social rate of discount; subject to two constraints:

$$(5.2) \quad \dot{W} = W \cdot (\dot{w}/w - F - M) \quad (\text{cf. Eq. 4.13})$$

$$(5.3) \quad 0 \leq F \leq F_{\max}$$

The upper limit on F is imposed to exclude an instantaneous harvesting of the entire biomass, but is conceived of as being "very large".

The Hamiltonian function is:

$$(5.4) \quad H = F \cdot (W - C) \cdot e^{-\rho t} + \mu \cdot (\dot{w}/w - F - M) \cdot W.$$

According to the maximum principle, fishing mortality should be controlled in such a way that the Hamiltonian function is maximized with respect to F at every point in time. As H is a linear function of F this means:

$$(5.5) \quad \begin{aligned} F &= 0 \text{ when } \mu e^{\rho t} > 1 - C/W \\ 0 \leq F \leq F_{\max} &\text{ when } \mu e^{\rho t} = 1 - C/W \\ F &= F_{\max} \text{ when } \mu e^{\rho t} < 1 - C/W. \end{aligned}$$

The rate of change of the costate variable is

$$(5.6) \quad \dot{\mu} = -\partial H / \partial W = -\mu e^{-\rho t} - \mu \cdot (\dot{w}/w - F - M).$$

According to Fig. 5.1, $W < C$ for $t < t_1$ and the instantaneous yield per unit of F is less than the cost per unit of F . No fishing is therefore optimal, but if any fishing will ever be profitable, (5.5) will hold with equality for some $t \geq t_1$. At that time there is "non-uniqueness of flow" (cf. Shell 1969); i.e. the momentary optimum value of F is indeterminate. However, any optimal dynamic pattern of fishing must satisfy the condition that the increase in profits from deferring the harvest be no greater than the return from investing the profits from fishing *now* rather than later. This condition makes it possible to determine a unique optimal path of fishing which approaches the smooth control for which (5.5) holds with equality.

Differentiating (5.5) as an equality, inserting (5.6) and solving for W gives

$$(5.7) \quad W = \rho C / (\rho + M - \dot{w}/w),$$

which is shown as locus α in Fig. 5.1. For $t < t_2$ it is in the SE-quadrant (not shown), approaching $-\infty$ as $t \rightarrow t_2$ from the left. For $t > t_2$ the locus α is in the positive quadrant, approaching $+\infty$ as $t \rightarrow t_2$ from the right, intersecting the natural biomass curve at $t = t_3$. For $t > t_2$ the relative growth rate of the natural biomass is less than the rate of discount ($\dot{w}/w - M < \rho$), but not until $t = t_3$ is the relative growth rate of its *net* value equal to the rate of discount. At $t = t_3$ (5.5) also holds with equality for the first time and the momentary optimum is non-unique.

Suppose now that $F = 0$ at $t = t_3$. In that case, (5.5) holds with inequality at $t = t_3 + \tau$, where τ is an arbitrarily short interval, and F should be made as

large as possible. But if $F=F_{\max}$ long enough to reduce the biomass below the locus α , it would violate the condition that no fishing should take place when the rate of return from deferring the harvest is greater than the marginal efficiency of investment. If that were the case we would have

$$(5.8) \quad F_{\max} \cdot (W_{t+\Delta t} - W_t) > \rho \cdot F_{\max} \cdot (W_t - C) \cdot \Delta t$$

where $W_{t+\Delta t}$ is the biomass at time $t+\Delta t$ if left unfished. The left hand side of (5.8) shows the increase in instantaneous profits from fishing if, instead of fishing at t , the stock is allowed to grow until $t+\Delta t$. The right hand side shows the return from investing the net profit from fishing at t .

Dividing by Δt and taking the limit as $\Delta t \rightarrow 0$ gives

$$(5.8') \quad \dot{W} > \rho \cdot (W - C)$$

which is equivalent to

$$(5.8'') \quad W < \rho C / (M + \rho - \dot{W}/W)$$

implying that the level of biomass is below the locus α . Therefore, harvesting will be deferred whenever the biomass has been reduced below the locus α . Conversely, if the biomass is above the locus α the inequality sign in (5.8'') is reversed, in which case it is more profitable to fish with maximum intensity and invest the profit than to postpone the harvest. The conclusion is that the optimal control of the biomass is "bang-bang" in the interval $t_3 - t_4$, with $F=F_{\max}$ when the biomass is above the locus α and $F=0$ when it is below that level. A "finely tuned" control would approach the smooth control, for which the biomass follows the locus α in the period $t_3 - t_4$ and (5.5) holds with equality.

By considering how the locus α changes in response to changes in cost and discount rate it appears that only the beginning of the fishery is affected, as the locus α always intersects the C-line at $t=t_4$ and fishing is unprofitable for $W < C$. For a given cost per unit of F , an increase in the rate of discount will displace both t_2 (when $\rho + M = \dot{W}/W$) and t_3 to the left (cf. Fig. 5.1). This accords with interpreting ρ as time preference; less willingness to wait causes the harvest to begin earlier. For a given discount rate, a decrease in cost would have a similar effect. The point t_2 is unaffected, but t_3 is displaced to the left, because the locus α shifts downwards. This is consistent with interpreting ρ as the social rate of return on investment. If less funds will be required to harvest a unit of biomass, the profit of harvesting a given stock will be increased. Since the rate of growth of biomass decreases with time, the return from deferring the beginning of the fishery will sooner become equal to the return from investing the profits from fishing (cf. 5.8).

Let us consider the limiting cases. As $\rho \rightarrow 0$, the locus α approaches a vertical line through t_4 . In this case the fishing period will be an interval

with $F=F_{\max}$, strictly containing the interval t_3--t_4 . Some fishing will then occur beyond t_4 . As $C \rightarrow 0$, the locus α approaches the right angle demarcated by the t -axis and a vertical line through t_2 , with optimal fishing being the shortest possible harvesting of the entire biomass. This reminds us of Wicksell's wine example, a case where harvesting costs may be ignored and the optimal age of the wine is given by $\dot{W}/W = \rho$.

We may now better understand why the optimal fishing strategy is *not* the quickest possible depletion of the biomass to an unprofitable level, except in very special cases. Given that fishing costs are proportional to the time that a certain number of units of fishing gear are kept in the water and given also that the probability of encountering a unit of biomass is proportional to the size (density) of the stock, it follows that the cost of catching a fish is inversely proportional to the size of the stock from which it is taken. It is therefore important to allow the year class to grow to maximum size, i.e. until its growth rate is zero. Discounting would seem to imply that the biomass be harvested earlier, i.e. when the rate of growth of its *net* value is equal to the discount rate. However, as soon as harvesting starts and the biomass is diminished the net value of each fish also diminishes, but would start to grow again at a higher relative rate than before if fishing were halted, as long as the year class has not attained maximum weight.

5.3. Optimal Fishing in a Multi-Year-Class Fishery

We shall now turn to consider a different problem and take a different approach. Most, if not all, fish stocks consist of a number of year classes which cannot be fished separately, except to a limited degree. This is certainly true of cod. What will be the optimal fishing strategy in this case?

In contrast to the single-year-class fishery, we shall assume that the length of the fishing period is given and equal to one year, while fishing mortality (effort) may be varied from one year to another. The problem to be considered is whether fishing should be stationary or periodic; i.e. alternating between years of high fishing intensity and intermittent years with no fishing at all. Our approach to this problem is to simulate a Beverton-Holt model of the Iceland cod. As before the objective is to maximize the present value of profits in the fishery. The objective function is

$$(5.9) \quad \sum_{t=1}^T (Y_t - CF_t) \cdot (1/(1+r))^{t-1}$$

where Y_t is given by the yield model in Chapter 4 (Eq. 4.4), T denotes time horizon, and r is discrete social rate of discount. We retain the assumptions from Chapter 4 of a constant availability coefficient, price of fish, cost per

unit of effort and annual recruitment.

In view of the analysis of the single-year-class fishery one might expect that the optimal fishing strategy would be to adjust gear selectivity in such a way as to take only fish of optimal age or older and harvest at a stationary rate. In the single-year-class fishery the optimal age is 9 years in absence of discounting (cf. Table 5.1). But in the multi-year-class fishery things are different. In Chapter 4 we explained the eumetric yield curve and why optimal age of recruitment to the fishery depends on the cost of fishing, regardless of discounting. Table 5.2 shows this very clearly. It summarizes the results of simulating the yield model, varying (knife-edge) selectivity of gear and calculating, first, the optimum stationary fishing mortality. The optimal gear selectivity with stationary fishing is to take fish aged 6 years or more when cost is 500 TMT (case A), but 7 years or more when cost is only 100 TMT per unit of F (case B). Second, Table 5.2 also shows the length and intensity of the fishing cycle giving the largest undiscounted profit. Clearly it is about as profitable not to fish at a stationary rate but in "pulses" of high intensity at regular intervals with years of no fishing in between. For fishing cost equal to 500 TMT per unit of F (case A) it is as profitable to fish every 5th year, selecting fish aged 5 years or older, as it is to fish at a stationary rate selecting fish 6 years and older. Similarly, it is as profitable in the lower cost case (case B) to fish every 3rd year as it is to fish at a stationary rate, selecting fish aged 7 years or older.¹

The reason why periodic fishing is as profitable as stationary fishing must be sought in the internal dynamics of the model, since there are no external disturbances that would cause variations in the optimal fishing rate. Considering the *instantaneous* production function, which is simply $Y = FW$, it is homogeneous of degree two and thus characterized by increasing returns to scale. The only way to increase the scale of the fishery --that is, both F

1 It is not wise to conclude that pulse fishing is "better" than stationary fishing on the basis of such small differences in the present value of profits as presented in Table 5.2, because of the inaccuracy resulting from i) disregarding the oldest year classes, ii) not taking into account that $\bar{w}_h$, the mean weight of fish of a year class of age h in a certain year, depends on fishing intensity during that year. Both of these make pulse fishing more profitable than is warranted. However, the assumption of a constant $\bar{w}_h$ is not as bad as an approximation to reality as it may appear. Although it is convenient here to regard fishing effort as being exercised at a constant rate throughout the year, it is not so in practice, as the availability of fish varies during the year. If a given stock is fished only a part of the year when it is most easily accessible, pulse fishing would mean skipping one or more "seasons", and it makes better sense then to regard $\bar{w}_h$ as a constant.

Table 5.2

Selectivity $\epsilon_i=0, \epsilon_j=1$	Strategy	Optimal F	"Profit per year" (TMT)
Case A: C = 500 TMT			
	Stationary fishing	0.11	110.134
i=1,2; j=3,...,15	Fishing every 11th year	1.70	125.659
	Stationary fishing	0.14	121.451
i=1,...,3; j=4,...,15	Fishing every 6th year	0.93	128.255
	Stationary fishing	0.16	128.371
i=1,...,4; j=5,...,15	Fishing every 5th year	0.84	131.653
	Stationary fishing	0.18	129.499
i=1,...,5; j=6,...,15	Fishing every 2nd year	0.36	130.238
i=1,...,6; j=7,...,15	Stationary fishing	0.18	123.990
.	.	.	.
.	.	.	.
	Stationary fishing	0.21	93.532
i=1,...,8; j=9,...,15	Fishing every 2nd year	0.41	92.805
Case B: C = 100 TMT			
	Stationary fishing	0.35	226.434
i=1,...,5; j=6,...,15	Fishing every 5th year	2.06	236.962
	Stationary fishing	0.42	233.022
i=1,...,6; j=7,...,15	Fishing every 3rd year	1.32	237.664
	Stationary fishing	0.47	230.992
i=1,...,7; j=8,...,15	Fishing every 2nd year	0.97	232.750
	Stationary fishing	0.53	221.947
i=1,...,8; j=9,...,15	Fishing every 2nd year	1.08	221.876

Footnote to Table 5.2: Profit per year is simply $(Y-CF)/n$, where n is the length of the fishing cycle; i.e. $n=2$ means fishing every second year. The age composition of the stock at the beginning of each "fishing year" is then

$$N_i = \text{Re}^{-(i-1) \cdot M - \epsilon_{i-n+1} \cdot F - \epsilon_{i-2n+1} \cdot F - \dots - \epsilon_{i-kn+1} \cdot F} \quad , \quad i - kn + 1 > 0$$

As the data show only weight at age up to age 12 (cf. Table 5.1), we have assumed that it stays constant beyond that age. The two cost figures considered correspond to 1.1 and 0.242 TMT per one MTH, which is to be regarded as extremely "high" and "low" respectively for this fishery, cf. Table 4.1.

and W at the same time --is to stop fishing and allow the stock to grow, only to hit it more intensively at a later date. The profitability of this may be seen by considering the case in which only year classes which have already attained maximum weight are selected (age 9 and older; $i=1,\dots,8$ in Table 5.2). To fish periodically would mean some loss of biomass, because no fishable year class is gaining weight, but it is nevertheless virtually as profitable to fish every 2nd year as it is to fish at a stationary rate.

But the case for periodic fishing can be made considerably stronger than this. "Knife-edge" selectivity of gear is impossible in practice. Variations in selectivity are accomplished by changing the mesh size of gill nets and trawls, and as the fish grow bigger it becomes more and more difficult for them to escape through the meshes. Each year class may therefore reasonably be expected to become gradually more and more vulnerable to the fishing gear as the fish grow older, and the probability that a fish will be trapped if it encounters a fishing gear will increase with age from 0 to 1. Estimations of this probability, or gear selectivity parameter, show that it increases gradually over a number of years (cf. Chapter 4 Fig. 4.2). Simulations of the fishery for Iceland cod, using estimates of gear selectivity (Clayden 1972) showed that pulse fishing was clearly superior to stationary fishing (Table 5.3).¹

Table 5.3

Strategy	Cost per unit	F Optimal	F "profit per year"	Improvement
Stationary	500 TMT	0.13	117.606 TMT	
Periodic every 6th year	500 TMT	0.87	122.793 TMT	4.5%
Stationary	100 TMT	0.22	185.716 TMT	
Periodic every 9th year	100 TMT	2.83	210.344 TMT	13.3%
Stationary	0	0.27	210.052 TMT	
Periodic		$\rightarrow \infty$		

By comparing the results shown in Tables 5.2 and 5.3 it is clear that the main reason why pulse fishing would be preferable to stationary fishing, under the assumptions made at the beginning of this section, is the indiscriminate fishing of young and old year classes, due to imperfect control of gear selectivity. In the absence of optimal "knife-edge" selectivity, stationary fishing removes a considerable proportion of each year class before it attains

¹ $\epsilon_1=0, \epsilon_2=0.03, \epsilon_3=0.3, \epsilon_4=0.85, \epsilon_i=1, i=5,\dots,15.$

optimal age, the more so the greater fishing intensity is. This is mitigated by pulse fishing, as it allows some year classes to grow beyond the (inoptimal) age of recruitment to the fishery, before being fished.

Table 5.3 also shows that the cost of fishing is an important determinant of both the frequency and intensity of the fishing cycles. The profitability of periodic fishing increases as fishing costs fall, which is not surprising, given that low cost per unit of fishing mortality implies high stationary fishing intensity and a substantial depletion of each year class before it reaches optimal age. For the same reason the interval between fishing pulses increases as the cost per unit of fishing mortality falls, as a heavily decimated stock will need a long moratorium to replenish itself.

In order to deal with periodic fishing when the future is discounted it is necessary to take explicit account of the transitory phase from one fishing strategy to another and the effect of discounting on the optimum stationary rate of fishing (cf. Chapter 2). Assuming that the exploitation starts with a virgin stock, the optimum fishing mortality when discounting at 10% is 0.23 and 0.50 for cost per unit of fishing mortality equal to 500 and 100 TMT respectively. Thus the effect of discounting is to displace optimum fishing mortality beyond its maximum sustainable yield level (0.27 for $\lambda=15$) when cost is low, as noted in Chapter 2, owing to the profit to be obtained from an intensive exploitation of the virgin stock. If now a transition from stationary fishing with cost equal to 500 TMT per unit of fishing mortality and $F = 0.23$ were to be made, it would increase the present value of rent within a time horizon $T = 40$, discounting at 10%, as shown in Table 5.4.

Table 5.4

Fishing every n 'th year with $C = 500$ TMT

n	F	Present value of rent	Gain
1	0.23	1006.914 TMT	
2	0.32	1116.128 TMT	10.8%
3	0.52	1126.393 TMT	11.9%
4	0.71	1135.931 TMT	12.8%
5	0.92	1133.687 TMT	12.6%

According to Table 5.4, periodic fishing every 4th year would increase the stream of profits by 12.8% over a 40-year period, compared to continued sustained fishing. Comparing Tables 5.3 and 5.4 indicates that the effect of discounting is to shorten the interval of waiting between fishing pulses as expected, and thereby also to reduce the intensity of each fishing pulse.

5.4. The Impact of Cost, Discounting and Natural Fluctuations

In this section we shall consider how natural fluctuations, cost and discounting will affect the optimal pattern of fishing. "Natural fluctuations" will be produced by replacing constant recruitment during the first half of the 40-year period by estimated deviations of recruitment from its average 1946--1966, with the age composition of the stock at the beginning of the period being given by estimate pertaining to 1946 (Clayden 1972). To economize on calculations the last three year classes were deleted from the model, so that it contains only 12 year classes as Clayden's original model. The upper limit of F was set at 1.

The optimization method used has been developed by H.H. Rosenbrock (Rosenbrock and Storey 1966), and was designed to cope with problems where the optimal values of the variables to be optimized are highly interdependent, resulting in a severely ridged response surface, as the case is here, cf. Table 5.5. The method is presented in an Appendix to this chapter.

Run 1 maximized the objective function for opportunity cost at 500 TMT, initial stock determined by $F = 0.14$ over the life-span of the fish, constant recruitment and discounting at 10%. The resulting pattern of fishing is shown in Fig. 5.2 and indicates a biannual fishing cycle.¹ The initial intensive exploitation is caused by discounting, which implies a higher optimal sustained fishing mortality than no discounting (cf. Chapter 2).

Run 2 maximized the objective function under the same assumptions about cost and discounting, but with "natural fluctuations". The resulting pattern is shown in Fig. 5.3. Total catch was increased from 5703.4 TMT to 6520.1 TMT and the present value of profits from 593.8 TMT to 630.0 TMT.² The same general conclusions about the relative merits of periodic versus sustained fishing as in the constant recruitment case are also valid here. But there is a marked difference in the optimal fishing patterns. The exogenous fluctuations in recruitment generate much more irregular and wide variations in fishing effort than does a constant pattern of recruitment. The uniqueness of this pattern may be seen from Fig. 5.3, which also shows the optimal pattern of fishing

1 This is not in perfect agreement with the result in the previous section, which showed a fishing cycle of four years. Note however the differences between the two simulations. In Section 5.3 the fishing cycles were all identical; in this section each cycle is determined by the optimization run. Secondly there are only 12 year classes in the present model, as against 15 in Section 5.3.

2 Simulations show that 593.8 TMT is the maximum present value of profits for the 40 year period. Optimal stationary F is 0.14 in this case.

Table 5.5

Parameters as in run no.	F-values as in run no.				
	1	2	3	4	5
1	1131.9	1057.8	1083.1	693.4	915.9
2	564.9	630.0	573.8	-19.1	586.0
3	632.2	613.3	720.0	116.0	484.8
4	1375.4	1204.1	1263.4	1607.5	1008.9
5	2982.1	3264.6	3186.3	536.2	3530.6

The matrix shows present value of resource rent. It has dominant diagonal elements, which is consistent with that all runs were in fact converging on a global maximum. Some values of a given row are however not very different, which indicates a ridged response surface.

Table 5.6

Run no.	Configuration of Parameters			
	C	r	Recruitment	Initial Composition of Stock
1	500	0.1	Constant	Determined by $F=0.14$ over λ years
2	500	0.1	Varies year 1 thru 21	Estimated for year 1
3	500	0.1	Varies year -1 thru 21	Estimated for year -1
4	100	0.1	Varies year 1 thru 21	Estimated for year 1
5	500	0	Varies year 1 thru 21	Estimated for year 1

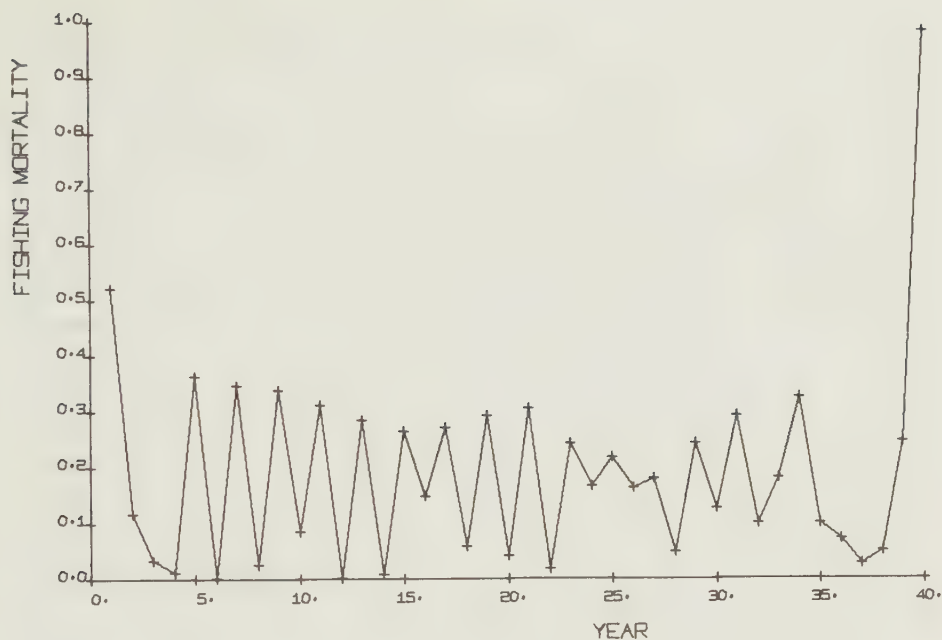


Fig. 5.2

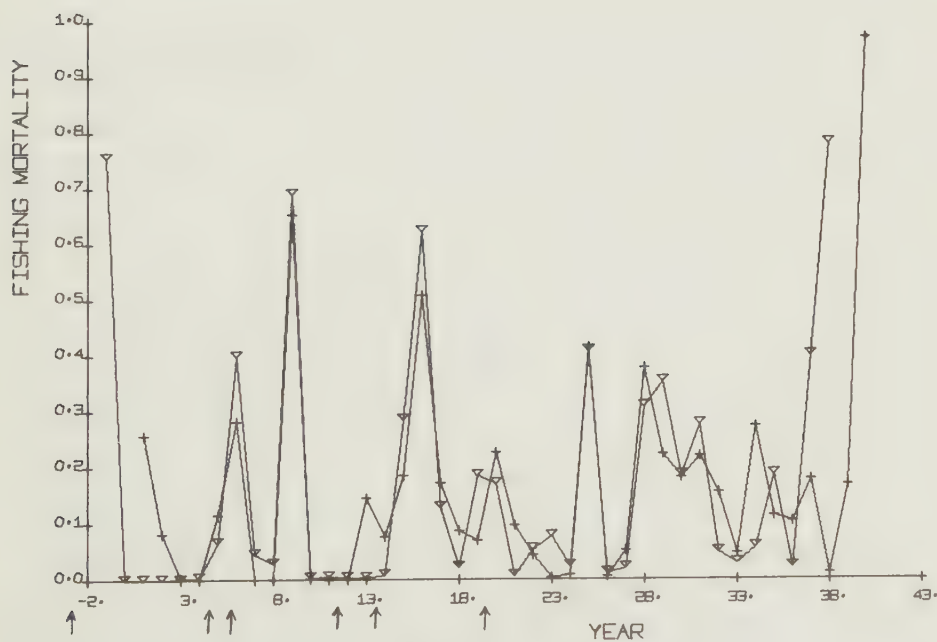


Fig. 5.3

when it was started two years earlier, changing the initial composition of stock accordingly.

A straightforward hypothesis is that the appearance of strong year classes has something to do with the effort peaks shown by the optimization run. The data show recruitment above average at the end of years -3, 4, 5, 11, 13 and 19, as indicated by arrows at the bottom of Fig. 5.3. The optimal fishing pattern shows effort peaks in years 1, 6, 9, 13, 16, 20 and 25, disregarding the last part of the period. Starting the fishery two years earlier reproduces the peaks in years 6, 9, 16 and 25; tilts the peak in year 20 to year 19; displaces the peak in year 1 to year -1, while the remaining one is not reproduced and is generated by the endogenous fluctuations of the system. The displacement of the initial peak may be explained by the fact that the initial stock in 1946 was at a very high level of abundance, owing to the absence of non-Icelandic vessels during World War II. The remaining peaks that are produced by both runs correspond to the number of strong year classes, allowing for that the strong year classes of years 4 and 5 should not be expected to give rise to two distinct effort peaks.

The time that lapses between the recruitment of a strong year class and the effort peak associated with it varies in length. It is usually 4-6 years, but as long as 8 years for the first strong year class; we shall refer to this as the *waiting period*. It is rather vaguely determined and does not correspond to the optimal age of the fish in a single-year-class fishery, which is more than 6 years after recruitment (age 7) when the discount rate is 10% according to Table 5.1. The reason will become clear as we now turn to consider the effect of lowering the opportunity cost.

In run 4 opportunity cost was changed to 100 TMT per unit of F, which is a very low figure. The optimal pattern of fishing is shown in Fig. 5.4. There is now a much more uniform length of the waiting period, and it is also in much better agreement with the optimal age of the fish in a single-year-class fishery. The reason is that the strong year classes are much more important as determinants of the size and growth of the total stock in this case. Suppose that a strong year class enters the exploitable phase, i.e. reaches the age of full selection by the fishing gear shortly after the end of a fishing period. It is in itself desirable to wait for this strong year class to reach optimal age, but there are other things to be considered: The gain in weight that the strong year class is capable of attaining must be compared to the loss of biomass through the death of old, slow growing fish. If the preceding fishing pulse was of short duration and low intensity as the case is when cost is high (cf. Fig. 5.3), there will be a relatively large number of

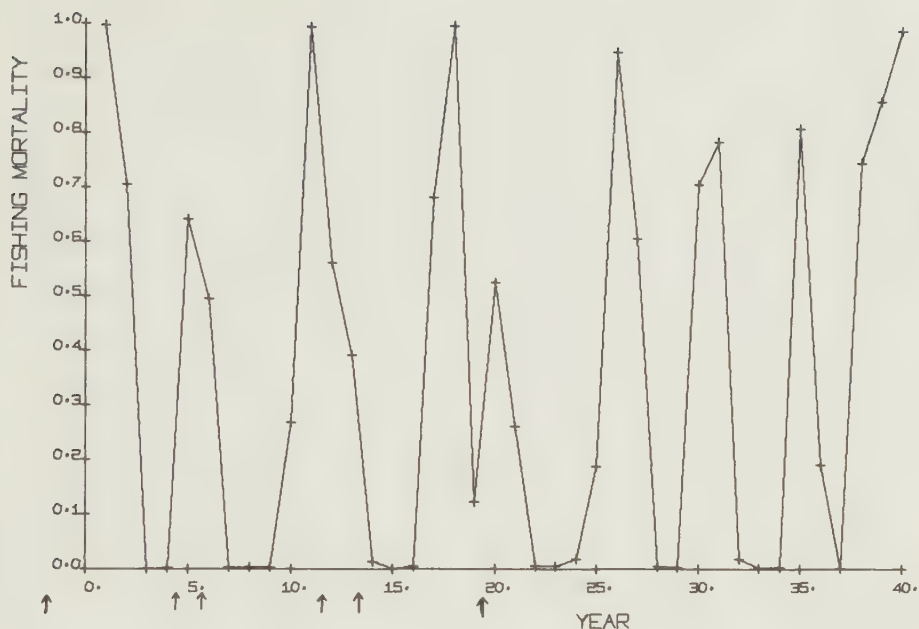


Fig. 5.4

old, slow growing fish in the stock, so the losses from waiting will outweigh the gains long before the strong year class reaches optimal age. This may be contrasted with the case when cost is low (Fig. 5.4) and the preceding fishing pulse was of long duration and high intensity. In that case there will be relatively few old, slow growing fish in the stock, and the gains from waiting will outweigh the losses until the strong year class has grown close to optimal age.

Hence, the result from the single-year-class model in Section 5.2 that decreased cost will lower the optimal age of the fish does not mean that it will shorten the waiting period for large year classes in a multi-year-class fishery, or increase the frequency of the fishing cycles in the absence of fluctuations; in Section 5.3 the contrary was shown to be the case.

One might expect that the discount rate would be a very important determinant of the optimal fishing pattern, as the occurrence of strong year classes obviously is, and time preference in turn determines the willingness to wait for the strong year classes to grow. Yet this is not the case, at any rate not in the interval 0--10%. No discounting produces a pattern not very different from the one corresponding to a 10% discount rate (cf. Fig. 5.3 and 5.5), and the effort peaks in the first half of the period containing the na-

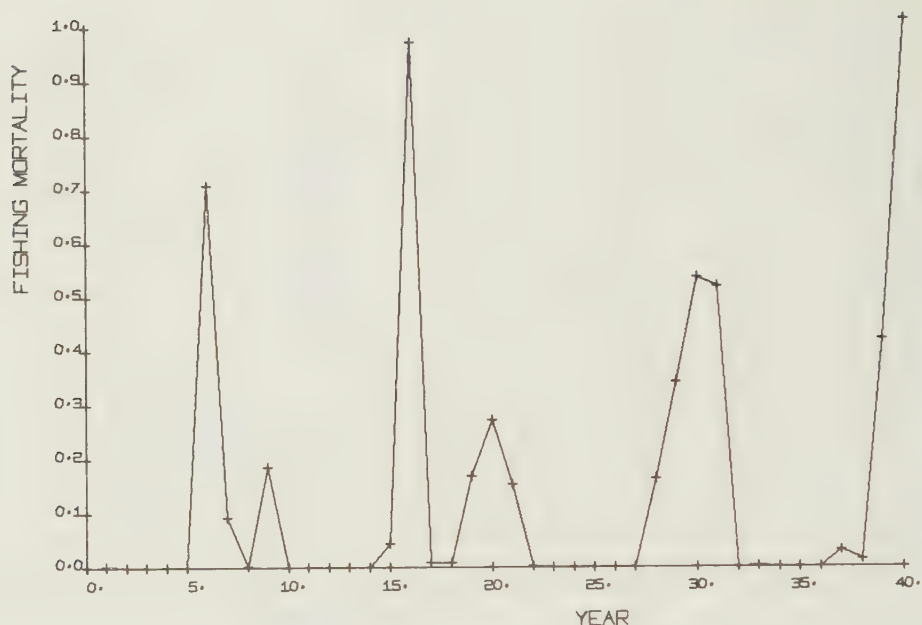


Fig. 5.5

tural fluctuations occur in the same years. Apart from that, the difference is that the effort peaks are fewer and more pronounced when there is no discounting, as expected. It appears that the cost per unit of F is a more important determinant of the optimal pattern of effort through its impact on the average rate of exploitation and thereby the *relative* strength of the year classes in the stock.

5.5. The Practicability of Periodic Fishing

Thus far we have assumed constant prices and opportunity cost, and perfect foresight. It has been shown that periodic fishing yields a higher present value of rents than stationary fishing for purely biological reasons; mainly because of indiscriminate fishing of different age groups, and because of natural fluctuations in year class size. We shall now relax those assumptions and attempt to come one step closer to the real world.

To deal first with perfect foresight, the assumption of a perfect knowledge of future recruitment that is implicit in the analysis of Section 5.4 may appear grossly unrealistic. Fortunately, it is not necessary to assume any super-natural insights on the behalf of the managing authority in order to claim some relevance for our analysis. Young codfish are not fully vulnerable to the fishing gear until some time after recruitment, which in the case of

the Iceland cod happens to be 4 years, according to the estimates used here. This time-lag may even be controlled to some extent by altering the selectivity of the gear. In the intermittent period the strength of the youngest year classes may be assessed, but such information certainly is costly, and it is an optimization problem in itself to what extent it would be worthwhile to obtain it. A simple game of annually revised planning of effort was played with the computer, assuming recruitment of all fish older than 3 years of age to be known with certainty, while other as well as future year classes were assumed of average strength. The optimal fishing pattern that resulted was very similar to the one yielded by assuming perfect foresight (cf. Fig. 5.6).

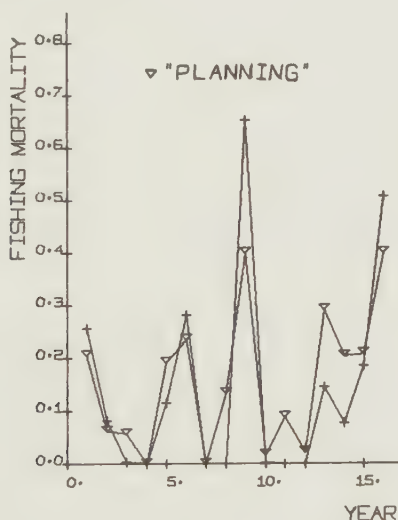


Fig. 5.6

The assumption of exogenous recruitment seems to accord well with the facts of the cod fisheries as they are known at the present time (cf. Chapter 4). Recruitment failure might occur if the spawning stock would be reduced too far, but this has not happened despite heavy and sustained overfishing. The average fishing mortality produced by optimal periodic fishing is less than the recent fishing mortality in the stock considered here. A more important objection is that violent changes in fishing intensity might cause environmental disruption. This is a biological problem which cannot be considered here, but some recent estimates of fishing mortality are about as high as the fishing pulses produced by our simulations.

To relax the assumption of a constant price of fish and cost per unit of effort, it may first be noted that changes in these parameters may either be

induced by varying the rate of exploitation, or they may be external to the industry and given by fluctuating market conditions or prospects in alternative fish stocks. Considering first induced changes it is meaningful to distinguish--somewhat loosely--between large and small fisheries. A small fishery is not likely to be capable of inducing great changes in fish price and may be expected to take it as a given parameter. On the other hand, a small fishery that is restricted to a given area--for institutional or technological reasons--is likely to have a limited range of opportunities. In the extreme case where there is only one stock of fish to be exploited in the area, one would expect that the value of the marginal product of fishing effort in its best alternative use is a rapidly falling function of the total effort diverted from the fishery. In that case stationary fishing would seem to be the best strategy, but the profitability of pulse fishing would increase with the number and size of alternative stocks that could be exploited in the area.

A large fishery that harvests a number of cod stocks would be more likely to reckon with a downward-sloping demand curve and thus reluctant, in the absence of shifts of the demand curve, to vary total output. On the other hand it would have the choice of alternating between various stocks. Pulse fishing might therefore be profitable, given that it would not lead to large fluctuations in total output.

In general, the greater the number of alternative stocks with identical characteristics, the better sense does it make to assume a constant opportunity cost of fishing, with given technology and market conditions. Although the production function which we have assumed implies a constant return to effort at every instant, as the level of biomass is given, diminishing returns to effort are inevitable in the long run as the stock is depleted. Therefore, the longer fishing effort must be committed to the alternative stock, the further will the catch per unit of effort be depressed for each additional unit of effort being transferred to the alternative stock.

Exogenous changes in cod price and opportunity cost may have a different bearing on the desirability of periodic harvesting, depending on whether they may be predicted or not. Foreseen changes influence the optimal fishing pattern in an obvious way, while uncertainty about future prices may or may not be in favour of periodic fishing, depending on the preferences of the authority playing the game of management. Exogenous changes in opportunity cost are the result of changed opportunities in alternative occupations in general, but the prospects in alternative fisheries will be most relevant. These may be either the result of market phenomena (i.e. price changes), or of natural fluctuations in stock size. The impact of such changes again depends on the

versatility of the fleet and the range of opportunities, but they certainly seem to be relevant for both large and small fisheries.

These remarks on the impact of exogenous changes perhaps convey the impression that market incentives will suffice to bring about an optimal fishing strategy in the absence of uncertainty. The fishing industry may certainly be expected to reallocate its effort to species the price of which has risen, but there is nothing to ensure that it will do so in the right proportion. The essence of optimal periodic fishing as well as optimal stationary fishing is to take future prospects into account; something that competitive fishermen with free access to common property fish stocks have very little or no incentive to do. This is also clear from the example in Section 5.3 where all prices were assumed constant over time and no exogenous fluctuations in stock abundance allowed. In that case there is no incentive for a small fishing firm to vary its fishing effort, and yet the optimal strategy was to alternate between years of "heavy" and "light" fishing (cf. Fig. 5.2). In addition there is the tendency to overcapacity and dissipation of rent prevalent under this regime. The arguments in favour of sole ownership or central control of the fishery are in no way weakened by relaxing the assumption that optimal fishing is stationary.

It seems therefore, that periodic fishing might be a preferable strategy for both a small and a large fishery. In a large fishery, demand relations are likely to constrain the variations of total fishing effort, but a more or less constant output might be achieved by rotating between different stocks. A highly mobile fleet, fairly independent of land bases, could practise periodic fishing with regard to unit stocks, taking maximum advantage of the natural fluctuations in stock size. This is not to say that such a fleet is necessarily superior to the more traditional fleets, as there may be a cost differential to its disadvantage. We shall consider this question in the next section.

A small fishery with limited opportunities might also find it to its advantage to vary the effort allocated to the cod fishery within limits dictated by circumstances in time and place. Total fleet size may be varied by controlling investment, and to the extent that alternative species exist, it could take advantage of exogenous fluctuations in opportunity cost or cod price. Nothing or very little need be forfeited by neglecting the cod fishery for some time when prospects are good in say, the capelin fishery, as the cod stock will replenish itself in the meantime, improving the prospects in the cod fishery.

5.6. Periodic Fishing of the North Atlantic Cod

5.6.1. Fleet Mobility

As mentioned in Chapter 4, several independent stocks of cod may be identified in the North Atlantic area. One possible approach to management is therefore to manage each stock independently and adjust fishing effort devoted to each stock to take the optimal catch that it is capable of sustaining in the long run. This is also the approach which has been adopted in the past; while it has been recognized that the approach must be comprehensive enough to embrace all fisheries exploiting one and the same stock, the discussion pertaining to optimal (or less inefficient) exploitation has been in terms of stationary fishing mortality suffered by each stock.

The analysis in this chapter suggests that a much more comprehensive approach to the management of these fisheries may be called for. The fact that the abundance of the various stocks fluctuates for environmental reasons beyond human control suggests that optimal fishing in the whole North Atlantic area implies rotation of fleets between the various stocks in order to take maximum advantage of these fluctuations, leaving some stocks "in fallow" to replenish themselves while others are being exploited all the more intensively.

Rotational fishing in the North Atlantic area would require a fishing fleet with a high degree of mobility; that is, a fleet which may be diverted from the Barents Sea to the Grand Bank or West Greenland according to the fishing prospects in each area. Such a fleet must have facilities to process the fish at sea and be fairly independent of land bases, but at the present time most of the catches of North Atlantic cod are taken with more "traditional" fleets returning to their home base to land the catch after each fishing trip, selling the fish fresh, either for direct consumption or to factories which process it into various final products.

Obviously, a switch to more mobile fishing fleets would have wide repercussions for the economies around the North Atlantic which are highly dependent on fishing industries owing their existence to the proximity to the fishing grounds. If indeed these fishing grounds could be exploited as economically by "floating factories", these North Atlantic fishing communities might lose a lot of their comparative advantage, with far reaching consequences for their industrial structure and their standard of living. Recently, fishing fleets from such far away places as Rumania and Bulgaria have begun to exploit the Northwest Atlantic cod stocks. Although this need not imply that these countries in fact enjoy a comparative advantage in this industry but may rather reflect a reluctance to extend foreign trade, it is at any rate a good example that fish consumers may be supplied by distant water fishing fleets from any

country as well as by fishing industries and fleets based in reasonable proximity to the fishing grounds.

Without establishing fishing bases in foreign countries, distant water fleets processing the catch at sea constitute the only possible way for countries situated beyond some critical distance from the fishing grounds to participate in the fisheries there. Such fleets, if any, would be expected to practice periodic fishing, and indeed they do move from one stock to another, although in response to seasonal fluctuations in availability rather than to annual fluctuations in abundance.¹ "Coastal" fishermen from countries in immediate vicinity to the fishing grounds who rely on vessels with a much more restricted range of operations frequently resent this, less able as they are to move on to another area with higher catches per unit of effort once their home grounds are depleted, and also simply because the distant water fleets compete with them to catch the same fish. Notwithstanding this conflict of interests between fishermen of different nationalities, we shall address ourselves to the question whether a single authority with a mandate to manage the cod fisheries in the whole North Atlantic area would prefer periodic fishing by highly versatile fleets to more traditional methods. If periodic fishing did in fact yield a larger stream of rents than the more traditional methods, it might be practiced by fishermen of any nationality to their own benefit. On the other hand, if fishing with more traditional vessels is more profitable, international trade and competition among fish suppliers would be expected to transfer some of that benefit to fish consumers through lower prices.

We shall in the following discussion distinguish between two types of fleets; "mobile" and "immobile". This terminology may put some strain on the reader's patience and intuition, as he may side with the delegate to a technical conference on fisheries who confessed that he was unaware of the existence of immobile fishing fleets. Nevertheless, this terminology has become established among experts on fisheries, who by mobile fleets mean vessels fairly independent of land bases and which could remain on the fishing grounds for a very long period of time; that is, months or years, rather than days or weeks as the immobile vessels. Mobile vessels are either equipped to process the catch on board up to the stage of the final product sold to the consumer, or else supported by factory ships.

5.6.2. The Cost of Mobility

Obviously, the cost differential between a mobile and an immobile fleet is a major determinant of the profitability of periodic vis-à-vis stationary

¹ Cf. Anon. (1972).

fishing of each stock. While periodic fishing may be capable of giving a larger total catch, it will nevertheless yield lower rents if the cost per unit of effort for a mobile fleet is sufficiently higher than for an immobile fleet. Gulland and Robinson (1973) assert that the operating costs of a mobile fleet are twice as high as for an immobile fleet. A detailed investigation of fishing costs for different fleet categories is too comprehensive to be attempted here, but the data on the North Atlantic cod fisheries seem to support a cost differential at least as great as that. We shall proceed by assuming a cost differential of this magnitude between the "mobile" and "immobile" alternative facing a hypothetical management authority, in an attempt to throw some light on the existence or non-existence of benefits to be obtained from periodic fishing with mobile fleets. As will be demonstrated below, this cost differential is sufficient to destroy the advantage of periodic fishing in terms of the present value of rents.

Looking at the catches per unit of effort for the English fleet (Table 4.1), it is immediately obvious that they are related to the distance from England. On the average they are lowest at the Faeroe Islands (0.405), followed by the grounds off Iceland (0.640) and Northwest Norway (0.645). The Barents Sea (0.812), Bear Island (1.155) and East Greenland (1.185) areas take an intermediate position, while the distant waters of Southwest (1.626) and Northwest Greenland (1.669), the Grand Bank (1.394) and the Labrador/Newfoundland area (1.674) on the average show much higher catches per unit of effort. This is not surprising; if a fleet with a home base on the east coast of England is to be indifferent between fish stocks located at different distances from its home port, it is necessary that the catches per unit of effective fishing effort (cf. Chapter 2) be higher in the more distant areas in order to cover the transportation cost differential.¹

Since the catch per standard unit of effective fishing effort simultaneously applied by any two fleets in a given area would be expected to be the same for both, we shall take the English figures as a reasonable proxy for the whole fleet. Table 5.7 shows that the mobile fleets take a larger part of the total catch than any other fleet category at Greenland and Labrador/Newfoundland, a considerable part on the Grand Bank, less still in the Barents Sea/Bear Island area, and negligible off Iceland and the Norwegian coast. Thus the mobile fleet is more predominant where the catches per unit of effort are highest, while it is virtually absent in the areas where they are lowest. This is

1 The number of hours fishing per day's absence for the English 500--900 Grt. trawlers drops from 8.25 at the Faeroe Islands to 4.36 at West Greenland and 3.99 at Labrador/Newfoundland (Clayden 1972).

Table 5.7

A table showing the percentage distribution of catches in 1970
by vessel category

Fishery	Non- Mobile	Part Mobile	Mobile
	<500 tn	501-900 tn	>900 tn
Barents Sea/Bear Island	36	42	22
Norway Coast	77	14	9
Iceland	71	25	4
Greenland, East & South	15	17	68
Greenland, West	25	34	41
Labrador/Newfoundland	18	18	64
Grand Bank	7	61	32

(Source: Anon. 1972)

consistent with the assertion that the cost of fishing effort with a mobile fleet is greater than for a more traditional immobile fleet. The virtual absence of mobile vessels in Icelandic and Norwegian waters may be explained by too low catches per unit of effort for the mobile fleet to cover its cost per unit of effort. As the immobile fleet seeks more distant waters, the transportation costs add heavily to the cost of effective fishing effort, and it is not profitable to deplete the distant stocks to as low catches per unit of effort as stocks closer to home. Therefore, the catches per unit of effort are sufficiently high in the more distant waters to allow the mobile fleets to operate without loss.

The reason why the opportunity cost of fishing in terms of life weight fish would be higher for a mobile than for an immobile fleet is probably for the most part due to higher processing costs at sea. The capital/labor ratio would be expected to be higher than that which is optimal in a land-based factory; the opportunity cost of labor would not only consist of wages but even the capital that is necessary to accommodate people at sea. In addition the wage rate may be expected to be higher at sea than on land in order to compensate for inconveniences. Energy may be bought more cheaply on land, and transportation of the final product may be more costly at sea due to transshipment under inconvenient circumstances and limited storage facilities.

Let us regard the mobile and immobile alternatives as two processes that produce identical final product to be offered to fish consumers, denoting its price by P , the price of the input fresh fish in the two processes by Q_M and

Q_{IM} , and the opportunity cost of processing by OC_M and OC_{IM} . If a fish producer were to be indifferent between the two processes, neither of which returns any overnormal profit, we would have

$$(5.10) \quad P - OC_{IM} - Q_{IM} = P - OC_M - Q_M = 0.$$

We have argued above that $OC_M > OC_{IM}$, which implies

$$(5.11) \quad Q_{IM} > Q_M,$$

that is, it is cheaper to buy the fresh fish from a mobile fleet, or the imputed price of fresh fish caught by a mobile fleet is lower than the price paid to the immobile fleet. If now the opportunity cost of effective fishing effort is the same for both fleets in terms of production forgone by allocating labor and capital to the fishery, it would nevertheless be higher for the mobile fleet once we reckon in terms of fresh fish, as the imputed price of fresh fish for the mobile fleet is lower than the price paid to the immobile fleet. The only way in which this could be compensated is that the mobile fleets fish more dense stocks that yield a high catch per unit of effort, where the immobile fleets suffer a transportation disadvantage.

Let it now be assumed that the cost per unit of effort for an immobile fleet is 0.6 TMT in every area considered, whereas it is twice as high, or 1.2 TMT for a mobile fleet. This latter figure is considerably lower than the catch per unit of effort in the distant waters at Greenland and Labrador/Newfoundland, and would thus imply some economic rent for the mobile fleets operating in those areas, while it is the same as the average catch per unit of effort on the Grand Bank.¹ The cost per unit of effort for the immobile fleet is about the same as the average catches per unit of effort for the English fleet at Iceland and Norway, but considerably higher than at the Faeroe Islands and thus higher than expected for a fleet that lands its catches in ports close to the fishing grounds. As fish consumers are concentrated in areas that are far away from the fishing grounds we shall be considering, it would be misleading to take the catch per unit of effort for the English fleet close to its home ports as an indicator of the cost per unit of effort--in terms of fresh fish--for immobile fleets in far away areas, because the price of fish will be lower in those areas due to transportation disadvantage. What

¹ Cf. Table 4.1. Note that our assumption of average vessel size off Labrador/Newfoundland and on the Grand Bank presented in the Appendix to Chapter 4 probably implies an overestimate of fishing effort in terms of ton-hours with respect to the data in the working group's report. This depresses the figures of catch per unit of effort, so that they are probably higher than shown by the last two columns in Table 4.1. This makes the assumption about the cost per unit of effort for the mobile fleet more cautious.

we are asserting is that it would be possible to exploit the fish stocks in the Barents Sea, at Bear Island, Greenland and Labrador by fishing fleets based in Northern Norway, Greenland and Newfoundland at an opportunity cost of 0.6 TMT, in contrast to an opportunity cost of 1.2 TMT if it were done by mobile fleets, given that the final product will be sold to the same fish consumers regardless of the fishing process involved.

5.6.3. Results of Simulations

Given this assumption about the fishing costs with mobile and immobile fleets, the periodic and the sustained fishing alternatives were compared by simulating seven fisheries associated with five North Atlantic cod stocks, as identified in the working group's report (cf. Chapter 4).¹ The simulations attempted to maximize the present value of profits from each fishery, with constant prices and discounting at 10%.² In the periodic, or "mobile", alternative, fishing effort was allowed to vary *ad libitum* between zero and one each year, whereas in the sustained, or "immobile", case, it was permitted to vary within limits of $\pm 20\%$ of an average value, specific for each stock and adjusted during the optimization run. With respect to the eastern stocks, however, fishing effort was permitted to be lower still during the first three years, as the initial estimates of biomass refer to 1960, prior to which these stocks were already overexploited (cf. Chapter 4). Tables 5.8 and 5.10 show the results with respect to the mobile alternative, while Tables 5.9 and 5.11 refer to the immobile one. Although neither run had quite met the convergence criterion when terminated, their progress had become slow enough to warrant the conclusions to be presented.

The value of the objective function, separable as it is into five parts, is shown at the bottom of Tables 5.10 and 5.11. The upper values refer to all 20 years, while the lower set of values was obtained when cutting off four years of the time series at either end, taking the sixth year as the first of discounting.³ This may give a more adequate basis for comparison because of the period of light fishing of the eastern stocks in the beginning in order to build them up from the preceding phase of overexploitation, and because the truncation of the time series shows an unreasonably intensive fishing during the very last years. A comparison of the values of the objective function for

1 Estimates of selectivity, weight at age, initial age composition and recruitment are taken from the working group's report. Our estimate of annual availability is explained in Appendix to Chapter 4.

2 The optimization method is the same as in earlier sections of this chapter (cf. appendix to this chapter).

3 I.e. the sequence of discount factors becomes $(1/(1+r))^{i-5}$, $i=5, \dots, 16$.

Table 5.8

		FISHING EFFORT				GRAND BANK	TOTAL
ARCTO-NORWEGIAN		ICELAND		GREENLAND	LABRADOR- NEWFOUNDL.		
COASTAL	DEEP-SEA	COASTAL	DEEP-SEA				
0.70	0.10	0.00	0.00	23.60	346.50	0.50	371.40
0.00	6.00	0.00	0.00	0.00	0.10	0.70	6.80
3.40	10.80	0.00	0.00	131.30	10.00	2.60	158.09
10.80	9.30	10.00	0.00	121.30	551.40	2.50	705.29
232.20	9.60	153.00	0.00	160.10	10.70	79.70	645.29
8.40	9.60	82.70	0.00	3.00	9.90	58.90	172.50
389.50	9.50	8.20	0.00	146.70	27.70	82.60	664.19
389.20	9.70	94.50	5.20	194.50	9.90	1.20	704.19
438.70	9.50	56.70	5.00	160.80	29.50	0.50	700.69
7.50	9.50	140.00	4.80	200.80	737.00	0.40	1100.00
236.20	9.50	164.50	69.40	165.20	246.80	74.40	965.99
369.70	9.50	78.40	4.40	70.40	259.50	15.80	807.69
478.40	9.50	168.90	4.90	17.60	82.00	108.30	869.59
676.90	9.70	107.40	0.30	6.10	222.50	0.40	1023.29
217.90	9.40	82.30	2.00	8.70	601.90	154.40	1076.59
35.00	9.60	147.50	4.00	9.90	569.80	4.90	780.69
0.00	9.50	158.60	1.60	9.00	237.40	18.20	434.29
9.90	332.50	160.80	7.00	12.50	297.60	25.40	845.69
282.80	388.50	163.70	15.10	9.20	0.00	93.90	953.19
373.60	411.50	171.00	37.40	595.10	999.90	202.10	2790.59

Table 5.9

YEAR			FISHING EFFORT				GRAND BANK
	ARCTO-NORWEGIAN		ICELAND		GREENLAND	LABRADOR- NEWFOUNDL.	
	COASTAL	DEEP-SEA	COASTAL	DEEP-SEA			
1960	56.60	143.40	98.60	12.30	164.60	425.90	51.70
1961	57.50	143.40	96.80	13.20	144.10	380.30	49.10
1962	57.20	143.40	105.60	6.40	164.60	365.40	49.10
1963	143.00	142.40	108.10	25.50	164.40	365.60	49.20
1964	175.50	142.50	211.60	66.30	137.30	365.80	49.20
1965	198.70	143.60	141.80	155.20	164.60	350.60	50.00
1966	197.60	143.60	143.60	153.60	164.60	350.50	49.70
1967	198.50	143.60	200.00	115.00	164.30	355.50	49.20
1968	197.60	143.60	191.70	115.90	164.30	375.70	49.30
1969	197.00	143.60	204.50	125.00	164.30	425.10	49.30
1970	198.80	143.60	204.50	125.20	147.50	395.50	49.60
1971	197.20	143.60	204.40	125.30	135.00	392.30	49.50
1972	197.70	143.60	204.30	125.50	135.00	358.00	59.80
1973	195.00	143.60	204.10	124.80	135.00	415.30	59.80
1974	195.90	143.60	202.00	126.20	135.00	417.30	60.70
1975	195.50	143.60	202.00	126.60	135.00	425.70	59.50
1976	195.00	143.60	202.00	127.90	163.30	421.50	59.70
1977	179.90	170.10	201.90	128.10	164.20	421.90	59.90
1978	179.80	169.90	201.80	128.00	162.60	423.00	60.20
1979	14.70	335.20	201.80	127.60	165.00	424.60	61.00

Table 5.10

CATCHES

ARCTO-NORWEGIAN		ICELAND		GREENLAND	LABRADOR-	GRAND	TOTAL
COASTAL	DEEP-SEA	COASTAL	DEEP-SEA		NEWFOUNDL.	BANK	
0.59	0.11	0.00	0.00	46.21	600.14	0.83	647.90
0.00	10.17	0.00	0.00	0.00	0.16	1.30	11.65
5.96	25.93	0.00	0.00	340.71	18.83	6.04	397.49
28.74	29.50	14.49	0.00	311.03	996.84	7.07	1387.69
787.68	35.28	243.53	0.00	372.28	18.16	233.69	1690.65
37.31	38.47	127.27	0.00	7.21	18.50	155.14	383.92
1986.59	36.70	13.48	0.00	420.51	58.02	190.26	2705.59
1767.82	35.28	162.82	6.75	543.28	24.42	2.79	2543.20
1643.25	36.01	99.97	6.80	389.69	91.98	1.48	2269.20
28.76	41.19	257.57	6.91	406.23	2307.71	1.60	3050.01
1086.21	42.93	297.32	95.15	260.09	690.21	332.12	2804.07
1870.80	35.77	140.05	5.80	92.87	720.66	70.28	2936.26
2393.73	22.93	308.12	6.37	22.04	242.64	454.85	3450.70
2155.71	11.37	192.55	0.37	8.13	773.43	1.56	3143.14
372.20	9.46	150.87	2.48	12.82	1968.54	528.67	3045.08
49.84	15.82	266.18	4.84	15.35	1462.93	13.81	1828.78
0.00	23.93	262.96	1.78	16.70	518.51	56.74	880.63
16.37	1049.25	246.16	7.41	29.61	610.06	83.39	2042.27
574.76	1145.66	231.55	14.98	24.13	0.00	281.78	2272.89
803.51	954.32	221.41	35.30	1221.20	1581.71	364.67	5182.15

DISCOUNTED RENT

4807.657 321.320 995.996 2266.102 582.141

DISCOUNTED RENT

6349.935 419.458 897.443 2431.772 743.107

Table 5.11

CATCHES

ARCTO-NORWEGIAN		ICELAND		GREENLAND	LABRADOR-	GRAND	TOTAL
COASTAL	DEEP-SEA	COASTAL	DEEP-SEA		NEWFOUNDL.	BANK	
45.18	154.33	76.44	8.09	290.43	718.14	78.38	1371.01
55.90	214.01	82.83	10.75	243.02	524.49	70.64	1201.66
73.21	286.49	102.96	5.74	308.26	466.79	76.74	1320.22
241.40	354.26	120.75	24.48	313.83	458.11	83.47	1596.32
363.05	399.97	252.53	61.98	248.98	443.09	90.22	1859.85
500.82	412.79	161.66	135.81	304.18	397.23	96.37	2008.88
595.66	405.78	157.07	142.22	354.16	403.84	96.72	2155.47
679.79	429.01	207.58	111.36	377.13	473.64	99.88	2378.42
687.59	482.40	195.47	115.82	355.53	642.47	114.58	2593.88
643.32	515.03	215.83	132.63	313.50	885.13	139.46	2844.93
639.67	488.06	226.03	129.96	233.13	891.01	157.28	2765.17
739.05	404.73	230.60	126.17	175.01	863.75	164.90	2704.25
872.23	290.63	232.02	122.70	146.86	800.86	202.80	2668.12
805.49	198.35	227.44	117.63	133.98	1027.79	195.89	2706.60
591.34	181.94	216.97	112.46	129.94	1057.56	188.43	2478.67
388.45	232.32	208.40	108.86	126.00	1013.33	171.03	2248.43
265.53	310.85	197.81	102.96	185.60	875.09	160.10	2097.98
220.32	463.16	187.63	100.33	227.67	757.15	149.54	2105.83
303.58	506.88	178.28	95.47	228.69	642.74	141.28	2096.95
40.60	976.24	171.76	93.91	256.88	545.84	125.39	2210.65

DISCOUNTED RENT

5217.679 897.407 1651.040 3720.556 758.688

DISCOUNTED RENT

5960.064 1033.890 1300.398 3297.059 748.623

both alternatives does not support the hypothesis that pulse fishing would be a preferred strategy. Only the Arcto-Norwegian cod shows some increase in the present value of profits when fishing is periodic rather than sustained. This is also the stock that displays by far the largest exogenous fluctuations in recruitment. The Grand Bank stock just about breaks even, while sustained fishing is clearly a more profitable alternative with respect to the others.

To this may be added that total effort and catches vary considerably in the pulse fishing alternative (Cf. Tables 5.8 and 5.10). An authority managing only one stock might reasonably regard the price of cod as given by the market, but a unified management of the whole area would presumably view the matter differently, taking price as a function of output and trying to prevent too wide fluctuations in the total catch. It is also open to doubt whether large variations of annual fishing effort would be feasible without running into problems with insufficient capacity in years of intensive fishing and excess capacity in slack years. If the optimizing problem were to be further constrained along these lines, it would reduce the optimal feasible value of the objective function in the mobile alternative.

Table 5.9 shows that fleets are assigned to both the coastal and deep-sea fisheries associated with each of the eastern stocks in the immobile case, although a greater part of the total catch is supposed to be taken in the coastal fisheries than presently is the case.¹ A comparison of Tables 5.8 and 5.9 shows that fishing effort is allocated almost exclusively to the coastal fisheries in the pulse fishing case. This is as expected, since a higher cost per unit of effort decreases the optimal rate of exploitation, thereby increasing the survival rate, while the selectivity pattern of the coastal fisheries is such as to take older fish than the deep-sea fisheries do. However, the bonanza created in the coastal fishery off Norway suggests that the model errs with respect to the catch prospects in this fishery. It is undoubtedly true that the catches in this fishery can be increased by decreasing fishing effort in the Barents Sea and at Bear Island, as demonstrated by the fact that both total catch and the catch per unit of effort were at their highest level in the immediate postwar years, after fishing in the Barents Sea/Bear Island area had virtually ceased during the war. There is quite a gap, however, between the record catch of 376.38 TMT in 1947 and the 2393.7 TMT shown by the model to have been possible in 1972. To the extent that the model is "too optimistic" in this respect the case for pulse fishing is further weakened.

The conclusion is, then, that periodic fishing with mobile fleets is not

¹ Cf. appendix to Chapter 4.

likely to constitute a more profitable alternative than sustained fishing of each stock with immobile fleets. To the extent that the cost differential assumed between mobile and immobile fleets is realistic, it is more than enough to destroy the advantage that periodic fishing has in being able to obtain a greater volume of catches. An argument that yet may be found in favour of mobile fleets is that the seasonal availability coefficient does not fluctuate in a uniform manner in all stocks. Therefore, it may still be preferable to let the fleets rotate between different stocks every year in response to seasonal availability, although each stock would be fished every year.

Rosenbrock's Optimization Method

The maximum (minimum) of the objective function $F(X)$, where X is a vector, is found by successive evaluations of $F(X + e_i V_i)$, $i = 1, \dots, n$, where the vector V_i belongs to the orthonormal set V^m . The step length in each direction, e_i , is determined in the following way: If the search in direction i was successful, X is replaced by $X + e_i V_i$ and e_i is multiplied by 3, but if unsuccessful, e_i is multiplied by $-1/2$. "Success" is defined as $F(X + e_i V_i) \leq F^0$, where F^0 is the best previously obtained value of the objective function. For minimization problems the inequality is reversed. When a successful step has been followed by a failure in every search direction i belonging to the orthonormal set V^m , a stage has been completed and a new set of orthonormal search directions is found by using the Gram-Schmidt orthogonalization theorem:

$$d_i = \sum_{i=1}^n e_i, \quad n = \text{number of search directions}$$

$$A_j = \sum_{i=j}^n d_i V_i^m$$

$$B_1 = A_1, \quad A \text{ and } B \text{ vectors,}$$

$$V_1^{m+1} = B_1 / \|B_1\|$$

.....

$$B_n = A_n - \sum_{i=1}^{n-1} (A_i V_i^{m+1}) V_i^{m+1}$$

$$V_n^{m+1} = B_n / \|B_n\|$$

$$\|B_i\| = \sqrt{\sum_{j=1}^n b_j^2}$$

$$(A_i V_i) = \sum_{j=1}^n a_j v_j$$

where b_j , a_j and v_j denote element j of vectors i , and the superscript m denotes the m 'th orthonormal set of search directions.

All search directions during the m 'th stage thus jointly determine the first search direction (A_1) during the $m+1$ th stage, each weighted by the total progress in that direction. Consequently, the first direction vector in the $m+1$ th stage (V_1^{m+1}) is parallel to the main direction of progress in the preceding stage, which is nice when the maximum lies along a ridge.

A two-dimensional example should clarify the procedure: Suppose that

the search started from a point like A in Fig. A 5.1 with search directions being $V_1 = (1,0)$ and $V_2 = (0,-1)$. As the diagram is drawn, $d_1 = d_2$, e.g. $d_i = 2$. It follows that $A_1 = (2,-2)$, $\|B_1\| = 8^{\frac{1}{2}}$ and $V_1 = (2/8^{\frac{1}{2}}, -2/8^{\frac{1}{2}})$, and the first direction during stage two is much better adjusted to the ridge than any of the previous two, facilitating farther process towards the optimum. A normal starting procedure is to use orthogonal unit vectors as search directions.

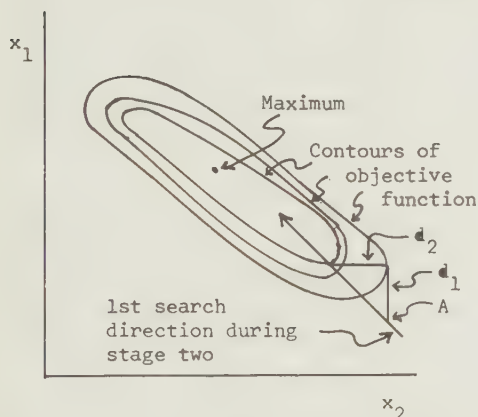


Fig. A5.1

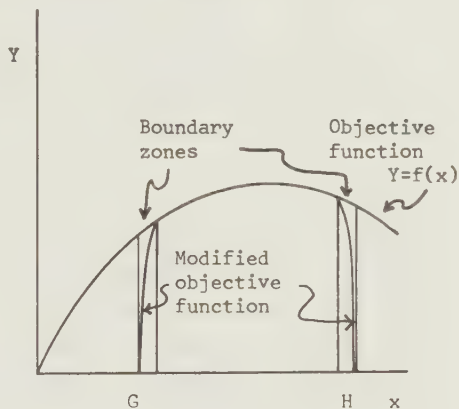


Fig. A5.2

In order to cope with constraints, an interval or "boundary zone" is defined in the neighbourhood of the constraint, in which the objective function rapidly approaches zero, cf. Fig. A 5.2, where G is the lower limit and H the upper limit. The width of the boundary zone in the figure bears no resemblance to the actual values used in the computations.

6.1. Introduction

As a rule, fish stocks are common property in the most general sense of the word, since their exploitation is free for fleets of any nationality. It is therefore not surprising to find that a fish stock has been overexploited at one time or another. What is more surprising is that overexploitation has in some cases been persistent for long periods (e.g. the North Atlantic cod, cf. Chapter 4). One would expect that the nations taking part in utilizing a given stock would find it in their interest to do so efficiently and cooperate to that end.

No matter how well understood and widely accepted the theory of rent dissipation under common property (cf. Chapter 2), there would still be a good reason to regard overexploitation as an unavoidable stage in the development of fisheries, because information on long term yield prospects is a by-product of the fishing activity itself. Although the long term yield could be predicted by yield models either of the Schaefer or the Beverton-Holt type, it is in practice impossible to estimate the biological parameters until the fishery has evolved through the successive stages of initial discovery, light exploitation and high yields per unit of effort, to overfishing.

Once overfishing is a fact there will be forces striving to preserve status quo, despite the possibilities of long term gains from efficiency. Those engaged in the fishery will fear losses from, or doubt compensation for, measures limiting fishing effort. A taxation of externalities in fisheries would, without compensation, make the owners of the variable factor(s) worse off than before. The short term gains from efficiency could be small, as the case may be in the North Atlantic cod fisheries (cf. Chapter 4). "Suboptimal" solutions may exist, such as mesh size regulations, which alleviate the problem temporarily, but do not result in efficient fishing in the long run.¹

The inertia that prevents efficiency will be a good deal stronger when it has an international dimension, owing to the inevitable conflict of inte-

¹ Cf. Turvey (1964), who concludes that mesh size regulation would be worthwhile only if producers' or consumers' surplus would be augmented, which is not possible in the long run, given that the demand curve is horizontal and that fishermen and fleets are homogeneous. If on the other hand the demand curve has less than infinite elasticity, then long term increase in catches that would result from increasing mesh size would also increase consumers' surplus. Similarly, if fishermen's opportunity cost is a rising function of their number, such mesh size regulation would increase intramarginal rents.

rests between the nations involved. The distribution of potential economic rent is an obvious bone of contention, but so is even the long term objective--that is, the optimal level of effort--as the economies involved will differ in terms of cost per unit of effort and time preference. As to the adjustment process towards long run optimum there will be disagreement to the extent that the economies differ with respect to alternative uses for their manpower and fleets. In addition, there may be disagreement on whether to set some sustainable annual yield as a target or to opt for pulse fishing of several stocks on a "rotational" basis. While "coastal" states are likely to prefer sustained annual yields from stocks close to their shores, utilizing their advantage of proximity to the fishing grounds, distant states may in turn prefer a rotational fishery, exploiting each stock intensively until the catch per unit of effort has been depressed far enough to render further exploitation uneconomic, then leave it "in fallow" and turn elsewhere. Although rotational fishing may not be the most efficient method (cf. Chapter 5), it could nevertheless be attractive for distant countries that are prohibited to set up fishing bases in coastal countries and reluctant to depend on foreign trade. Finally, a presumptive agreement among those who are engaged in a certain fishery at any given time may be unstable, as new entrants may consider themselves unhampered by any agreement among firstcomers.

These difficulties to obtain agreements on fisheries management within the existing framework of international law and the inherent instability of such agreements have led economists and jurists to consider alternatives to the present freedom of the seas. International jurisdiction over fish stocks, usually a single authority to manage world marine fisheries, seems to be the alternative favoured by most. (Cf. McDougal and Burke 1962, Christy and Scott 1965, Koers 1973). This may appear attractive for reasons of equity and would be expected--nay, is indeed conceived--to promote efficiency. Nevertheless, there is at present a strong tendency to circumscribe the freedom of the seas by extending the jurisdiction of coastal states, rather than, or parallel to, creating an international authority for their management. We shall in this chapter argue that this solution may be expected to be more efficient, and quite possibly more equitable as well. In Section 6.2 we shall consider the instrumentality--and limitations--of national fishing limits in promoting efficiency. In Section 6.3 we shall discuss the equity aspect. We conclude this chapter with a discussion of the probable effects of extended fishing limits with respect to the North Atlantic cod fisheries.

6.2. Fishing Limits and Efficiency

The conclusion that nothing less than a "World Fisheries Authority" is needed to manage fisheries is often based on biological arguments such as ecological interdependence of species and that fish are prone to lack respect for any such limits as governments may wish to draw on marine charts. Therefore, national property rights to fish stocks cannot be instituted, and one nation may cause serious external diseconomies to others by fishing stocks within its limits which are ecologically related to fish stocks outside those limits. To take one argument at a time and ignore ecological relations for a moment, it is quite true that it would not be possible to enclose all unit stocks within the jurisdiction of one coastal state only, but national property rights to a number of less migratory stocks could nevertheless be established by a suitable definition of fishing limits. Given a fish stock that does not migrate into the high seas or other nations' waters at any time, the coastal state would find it meaningful to attempt to control the exploitation of that stock, and an institutional framework for management is then provided by the coastal state's jurisdiction over its subjects and territory.

In cases where fish migrate out of one coastal state's waters, the only benefit that state would have from extending its fishing limits without further measures would be to give vessels flying its flag exclusive rights to fish within its own waters, but it would not be able to control the exploitation of the stock effectively. A general extension of fishing limits would nevertheless promote efficiency to the extent it would minimize the number of states with rights to exploit a given fish stock and facilitate agreement among them on its utilization. In the majority of cases there would be only two or a few states "sharing" each stock, compared to ten or more that are now at times involved in fishing a given stock. International management would then consist of regional agreements, in most cases involving cooperation of neighbouring states which are compelled to work together on a number of other matters as well.

The most far-reaching extension of fishing limits would be simply to divide the world's oceans between the coastal states. Any given fish stock would then become the "common property" of a well-defined number of coastal states that could bargain among themselves over its utilization. The management of world fisheries would then be a pyramid of regional management schemes, with the most extensive ones applying to the most migratory species or to cases where a number of coastal states are adjacent to the same continental shelf over which fish move freely. But short of that extreme solution, the question of drawing fishing limits in such a way as to maximize the number of stocks that would be enclosed is a question of the migratory habits of the

various species.

There are, broadly speaking, two categories with respect to migration; those that inhabit the waters above the continental shelf (demersal species) and those that roam over wide areas, perhaps from one continent to another (anadromous and pelagic species). The most sensible solution from the point of view of efficiency seems therefore to be the extension of fishing limits to the edge of the continental shelf, perhaps even including its slope down to the ocean floor.¹ The present trend to define fishing limits as N-miles from shore (or base lines), where N is a number divisible by ten or one hundred, has little else to recommend itself than being easy to memorize, although states with a very long coast line might in some cases be able to enclose even pelagic and anadromous species by a wide enough extension of their limits.

The ecological externalities argument is to some extent already answered. A wide extension of fishing limits would limit the number of states involved, and there would be an incentive for them to bargain for a solution. But although ecological relations between species are economically important in theory (cf. Chapter 3), the evidence of their being so in practice is notoriously scanty. Although this would probably change if fisheries will be extended to many more species than are being exploited at the present time and technological efficiency of fisheries increases further, it seems to be prescribing a too strong, perhaps deadly, medicine to institute a "World Fisheries Authority" to manage *all* marine fisheries. While all externalities would then be internalized, some losses of efficiency seem likely to result from the creation of such a huge administration as would be necessary.

This is not to say that national fishing limits are a perfect substitute for international management, but only that they could play a role as an integral part of a pyramid of management schemes, where the number of states participating in each scheme would be minimized, as necessitated by migratory habits of the species concerned and ecological relations, their nature and importance. A "World Fisheries Authority" would no doubt be useful for dealing with problems of global character, collecting data, sponsoring research and formulating general principles together with regional organizations, while each state would be responsible for the practical details of management. The fact that the nation-state is still the principal unit of lawmaking and law enforcement is of no little importance for achieving an efficient solution.

1 The continental shelf is itself an extension of the land mass, which in most cases slopes rather gently until there is an abrupt drop down to the ocean floor.

6.3. Fishing Limits and Equity

Even if there are arguments that favour a general extension of fishing limits for reasons of efficiency, it may appear grossly unfair to allow coastal states to appropriate resources that hitherto have been free for anybody to use. The expression "common heritage of mankind" is frequently encountered in discussions of ocean resources, and it is then more or less explicitly pronounced that they should continue to be a common property of mankind, but managed by an international organization. We shall not indulge in philosophical speculations on what is "common heritage of mankind" and what is not, and whether resources on land, under and on the seabed that are considered national or even private property therefore are not "common heritage". But it is a sobering thought that the only way for landlocked states--by some supposed to be disfavoured by the extension of coastal states' fishing limits--to share in the benefits from ocean resources is and will be by trading with those who live and work at, or on, the sea.

We shall in this section attempt to point out possible gains and losses resulting from an extension of coastal states' fishing limits. Let it be assumed that the extension encloses one or more unit stocks of fish within the limits of each coastal state. Suppose further that the fishery in any given area is conducted by fishermen from the coastal state and the rest of the world prior to fishing limits extension at time t_0 , that bionomic equilibrium has been established at t_0 , and that only fishermen from the coastal state are permitted to fish in its waters after the extension. Assume, finally, that the fish is sold to consumers in the rest of the world, and that no single coastal state considers itself a large enough part of the total fishery to wield any power over the price of fish.

The impact of fishing limits extension on the rest of the world will be dealt with in the following way: Suppose that a comparison is made between the actual state of affairs at $t > t_0$ and the bionomic equilibrium as if it had continued to prevail. If such a comparison were continuously made, it would be possible to arrive at a stream of benefits or losses, discounted over time, that would be a measure of the impact of extending fishing limits.

Generally speaking, this impact would consist of a multitude of effects on prices and quantities of all goods, induced by the transfer of resources and generation of trade flows, but only a few of all possible effects are likely to be of any importance. After they have been identified the problem may be tackled by partial equilibrium analysis.

Considering, first, the rest of the world, it is convenient to distinguish between two, perhaps overlapping, groups: fishermen (in a wide sense of the word,

including those who own capital in the fishing industry) and fish consumers. As far as the extension of fishing limits means an immediate exclusion of rest-of-the-world fishermen from coastal states' waters, they will have to find alternative employment for themselves and their capital. At the time of extension there will probably be a considerable difference between fishermen's actual income and their transfer earnings. Denoting this difference, or rent per unit of fishing effort, by V , fishermen's total loss of income at the time of extension is

$$\int_0^{f_0} V(t_0, f) df$$

where f_0 is the amount of resources that the rest of the world commits to fishing in bionomic equilibrium.

It is reasonable, to say the least, to expect V to be a function of time. Retraining of manpower is one reason, but more importantly we are comparing a given allocation of resources with another that would be the result of an institutional change at an earlier point in time. After the extension of fishing limits, the rest of the world will not transfer capital into assets specially designed for fisheries in foreign waters, unless leased. Since, in Marshall's words, skills at fishing are acquired and not the result of any special aptitudes, it follows that V is a decreasing function of time and falls to zero after a sufficient time has elapsed. At time t_1 the accumulated loss of income from not allocating factors of production to sustain fishing effort f_0 is

$$\int_{t_0}^{t_1} \int_0^{f_0} V(t, f) df dt.$$

Turning now to the fish consumers, it is permissible to ignore the effect of transfer of resources from the fishing industry on the prices of other goods and factors of production, as long as they are being transferred to many different uses and as long as unemployment of fishermen does not have any significant effect on aggregate demand. The effect on the price of fish is not negligible, however. Measuring this effect by the change in consumers' surplus we have at a given point in time:

$$\int_{p_0}^{p'} x(p) dp$$

where p' is the price of fish prevailing at that point in time, p_0 is the price in bionomic equilibrium, and $x(p)$ is the demand function for fish (cf. Fig. 6.1), assumed not to change with time. This is a measure of whether the fish consumers are better or worse off as a result of the extension of fishing li-

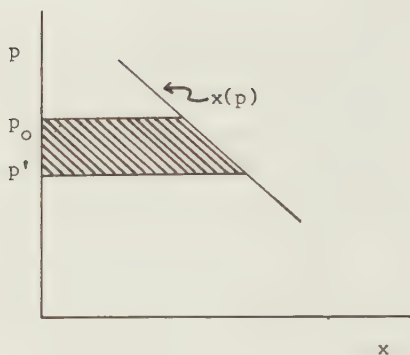


Fig. 6.1

mits. Note that x , the quantity of fish consumed in the rest of the world, is by assumption equal to the total catch. The accumulated effect on fish consumers at time t_1 is then

$$\int_{t_0}^{t_1} \int_{p_0}^{p_t} x(p) dp dt,$$

and the present value of the total impact on the rest of the world is

$$\int_{t_0}^{\infty} \left(\int_0^{f_0} V(t, f) df + \int_{p_0}^{p_t} x(p) dp \right) \cdot e^{-\rho t} dt.$$

It has already been argued that the first term within brackets will become zero after sufficient time has elapsed. The second term, the effect on fish consumers, is ambiguous however. Assuming that the coastal states will attempt to attain an optimal stationary yield, fish stocks will have to be built up to an optimal level. This can only happen through a moratorium or a temporary decrease in catches. The initial effect on consumers will therefore certainly be negative, as a less quantity of fish bought at a higher price means a loss of consumers' surplus. The optimal stationary yield may on the other hand be either greater or smaller than the bionomic equilibrium catch. If it is greater, the consumers' surplus will also be greater than in bionomic equilibrium, since the consumers are then able to buy more fish at a lower price, and it is therefore possible that the total impact on the rest of the world of extending coastal states' fishing limits is positive. The possibility of this outcome is of course strengthened to the extent that the comparative advantage of the rest of the world lies in the production of other things than fish, with its fisheries being subsidized and/or trade in fish hampered prior to fishing limits extension.

Considering now the coastal states, there is little doubt that they can be expected to gain from extending their limits. They will increase their catches at the expense of the rest-of-the-world fishermen, even if the total catch falls. The exclusion of foreign fleets suffices to bring this about, but the coastal states might also find it in their interest to increase their catches further by expanding fishing effort. There is, nevertheless, a slight possibility that extension of fishing limits will have an impoverishing effect on the coastal state, similar to the immiserizing growth case in international trade theory (Bhagwati 1958). Following Bhagwati, let us assume a coastal state that produces two goods, fish (exportables) and importables. For any stationary level of fishing effort applied by the rest-of-the-world fishermen there is a transformation curve showing the long term production possibilities for the coastal state in absence of technological progress and growth in factor endowments. Such a curve, T_1 , is shown in Fig. 6.2; note that it bends back toward the origin, because a transfer of factors from importables to fishing will ultimately reduce long term yields to such a degree that even the total catch accruing to the coastal state decreases. If then the rest-of-the-world fishermen are expelled from the fishing banks, this will increase the long term catches for any given size of the coastal state's fleet and thus displace the production possibility frontier to, say, T_2 in Fig. 6.2. The effect is thus similar to disembodied technological progress. But if the total supply of fish from all coastal states in the long run exceeds the total

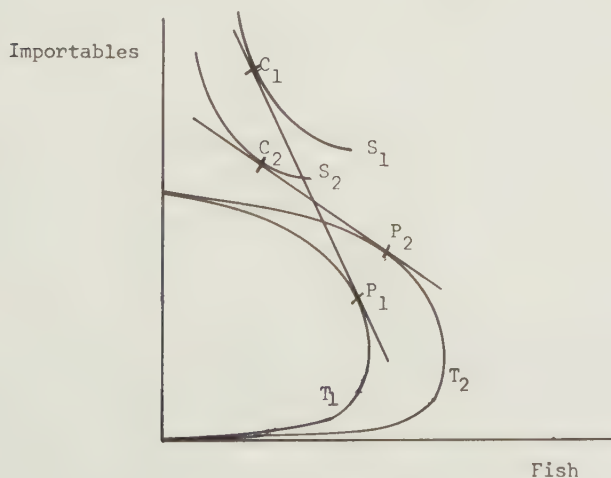


Fig. 6.2

catch prior to fishing limits extension and demand is inelastic, the final outcome for each coastal state could be a loss of welfare through deteriorating terms of trade. Suppose that the coastal state produced at P_1 and consumed at C_1 on Scitovsky frontier S_1 prior to extending its fishing limits, but ends up producing at P_2 and consuming at C_2 on Scitovsky frontier S_2 in a new equilibrium after the extension, exchanging more fish for less of importables. In that case the coastal state would be worse off than before.

The conclusion is, therefore, that the effect of coastal states' appropriation of fish stocks is ambiguous. It will in all probability benefit the coastal state, but the result could be the opposite. In particular, the extension of fishing limits might quite conceivably meet Pareto-based welfare criteria; i.e. that every nation involved would gain from the change, and that fish consumers in the rest of the world could compensate fishermen in the rest of the world for their losses.

This result ought not to be surprising. All that it amounts to is that as far as the extension of fishing limits facilitates more efficient exploitation of fish stocks, it generates benefits that will be distributed between producers and consumers through trade, resulting in a greater consumers' surplus if the resource is seriously enough depleted, and economic rents for fishermen, or fish exporting countries. It therefore largely misses the point to regard the extension of fishing limits as analogous to confiscation or nationalization of foreigners' property. If a mine or a firm is taken over by the host country, all the economic rent that it is capable of yielding is thereby transferred to the new owner and the previous owner effectively dispossessed. In the case of appropriation of fish stocks where the point of departure is bionomic equilibrium under common property, it is largely a question of *generating* economic rent and not to confiscate it from anyone.

In order to evaluate extended national fishing limits vis-à-vis international management in terms of equity, it would be necessary to have well defined alternatives to compare. The effects of extended fishing limits may be difficult to quantify and evaluate, but when it comes to "international management" without further specification the task is hopeless. No doubt it would be possible to dream up some arrangement which would, given some definition of equity, be superior to extending national limits, the distributional effects of which may be said to be accidental. But what would a "World Fisheries Authority" look like in practice? Would it be capable of exacting and redistributing the potential economic rents in world fisheries, or would it be a rubber stamp in the hands of the most advanced fishing nations and firms? How would economic rents be distributed? There is nothing to suggest that international management

would necessarily be more equitable than the extension of national fishing limits.

Natural resources are generally owned either privately by individuals or collectively by nations, and no one probably is prepared to argue that the endowment of resources is the way it is for reasons of fairness. Inasmuch as common property is not a principle to be upheld as such, even partially with respect to ocean resources, but rather by virtue of its bearing on the equitable distribution of income, however defined, the question becomes whether the extension of fishing limits would improve or worsen that distribution. We shall not pursue that matter here, but only observe that economically less developed nations would in many cases be among the gainers, e.g. the coastal states of West Africa, whereas industrially developed nations that engage in distant water fisheries would either have to give it up or else pay rents to the coastal states.

6.4. Fishing Limits and the North Atlantic Cod Fisheries

To return to the more specific question of the North Atlantic cod fisheries, it may first be observed that extended fishing limits would be particularly suitable to facilitate efficient exploitation of this resource. The cod is a demersal species that does not migrate very extensively, and a number of independent unit stocks may therefore be identified (Cf. Chapter 4). With regard to the stocks considered in Chapters 4 and 5, all of them would become the property of one or two coastal states, if their fishing limits were extended to the edge of the continental shelf.¹ The number of states that would have to come to agreement on the management of each stock would be greatly reduced, as there are now 14 member countries on the North East Atlantic Fisheries Commission (NEAFC) and 15 on the International Commission for the North West Atlantic Fisheries (ICNAF), the two organizations dealing with the political side of fisheries management in the area.² The number of countries with direct interest in the management of a given stock is sometimes no less than the total number belonging to each organization, and--it may be added--their number has tended to increase with time.

1 There are other stocks, not mentioned in chapter 4, such as in the North Sea and the Baltic Sea, where more countries are adjacent to the same continental shelf and would thus share the stocks that inhabit these waters.

2 Members of NEAFC are: Belgium, Denmark, France, West Germany, Iceland, Ireland, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, the UK, and the USSR. Members of ICNAF are: Canada, Denmark, France, West Germany, Iceland, Italy, Japan, Norway, Poland, Portugal, Romania, Spain, the UK, the US and the USSR.

As to the impact on countries excluded from these fisheries, it depends on the alternative employment for their fishermen and fleets, and the change in the total supply of fish. The versatile, long distance fleets fishing the western stocks could be diverted to other areas, although they would most likely yield less return, whereas the less mobile fleets fishing the eastern stocks would have little or no alternative use, as the areas within their range are already fully or excessively utilized. As the cod stocks are already overfished and it would be necessary to sacrifice near term catches in order to increase future profits, there need be no doubt that the excluded countries would suffer near term losses. As the yield curves for cod do not appear to have a very pronounced maximum, it is doubtful if a more efficient exploitation would result in an increased supply of fish in the long run, in which case fish consumers in distant countries would not benefit. It may therefore be expected that the benefits of more efficient exploitation will largely or wholly be captured by the coastal states themselves as rents.

The possible advantage of pulse fishing would of course necessitate an international management of the fisheries. It is doubtful that this would be the most efficient way of utilizing this resource (cf. Chapter 5), but the existence of national fishing limits would not by itself exclude that strategy, as the nations involved could agree among themselves on its implementation, if it appeared advantageous. But the existence of national property rights to fish stocks would evidently influence the distribution of benefits from such a policy.

An argument that presumably might be advanced against appropriating the cod (and other) stocks in this way is the risk of thereby also endowing the coastal states with monopoly power, by which they would be able to squeeze monopoly rents from consumers. That risk does not appear to be great. The largest stocks would be managed by Canada, Norway/USSR, Iceland and Denmark (Greenland), all of which are and would increasingly become net exporters of fish, except the USSR, or lease part of the fisheries. On the basis of the average annual catch of cod in the North Atlantic 1966--1970 these five countries would manage approximately 80% of the total catch. As far as this goes the prospects for a codfish monopoly are not exactly bad, but they become a lot gloomier when we consider that there are close substitutes to codfish. The capture of monopoly rents would therefore seem to necessitate collusion among fish producing countries on an unprecedented scale. On the other hand it is quite likely that cooperation between the coastal states on allocation of fishing effort would be advantageous, as it would enable them to adapt the time pattern of fishing to the fluctuations in year class size (cf. Chapter 5 on pulse fishing).

Chapter 7

CONCLUSION

Fisheries are one class of activities to which men can devote their efforts in order to improve their lot. The common property character of fish stocks implies that the uncontrolled market mechanism will not induce them to do so in right proportion vis-à-vis other activities. Empirical studies have provided many examples of this; our analysis here of the North Atlantic cod fisheries confirms that they are not an exception.

The fact that fish stocks more often than not are *even internationally* common property has undoubtedly delayed a regulation of their use, as new political institutions--or international laws--have to be created for that purpose. At the same time, improvements in technology have aggravated the problem by making additional stocks economically attractive, or lowering the relative cost of fishing and thereby encouraging further reduction of exploited stocks. It is against this background that the present trend to extend fishing limits must be seen. No one need doubt that this is conceived for the benefit of the coastal states themselves, but economic analysis shows that the outcome will most likely constitute an improvement compared to the present situation, not only for the coastal states but for the world economy at large.

The evaluation of fisheries vis-à-vis other activities clearly requires an economic analysis. Nevertheless, fisheries management is often discussed--or even attempted--in quantitative biological terms. The reason is understandable; the most important economic constraint is the growth capacity of the fish stock, given that sustainable yield in some sense and not extinction is desirable. As any stationary sustainable yield (except the maximum) can be taken with two different levels of fishing effort, it sounds reasonable rather to take a given yield with less effort, which is to say that effort should not exceed that which is required for taking the maximum sustainable yield. On the other hand, some loss of biomass is clearly involved in taking less than the maximum sustainable yield. Hence the preoccupation with regulating fishing mortality in such a way that maximum sustainable yield is taken.

Although in practice the yield curve may not be known with enough certainty to distinguish clearly between the maximum sustainable yield and optimum economic yield in terms of fishing mortality, the two are quite different conceptually. Optimum economic yield takes explicit account of fishing costs, ~~is~~ in absence of discounting always less than maximum sustainable yield and implies less fishing effort as well. Dynamic analysis shows that, given a positive rate of interest, the optimal fishing effort may exceed the maximum sus-

tainable yield level, but there may of course be biological reasons for not depleting fish stocks as far as that, such as recruitment failure or some other disastrous effect (cf. the analysis of the backward-bending yield curve in Chapter 2). Unfortunately we would not know until afterwards. In the cod fisheries which we have considered it seems highly improbable that the configuration of fishing costs and discounting is such as to imply optimum fishing effort in excess of maximum sustainable yield level. The recommendation of fishery biologists to reduce fishing effort at least to that level is therefore well taken.

An attempt to manage fisheries by controlling fishing mortality only may easily prove economically ineffective. Competition among fishermen may lead to shorter and shorter seasons and overcapacity, with economic rent being dissipated through increasing costs without increasing annual fishing mortality (cf. Crutchfield and Pontecorvo 1969).

By definition, economics of fisheries is less than a purely abstract subject. Some elementary knowledge of fishery biology is necessary to arrive at meaningful conclusions. Without a close connection with the work of fishery biologists, the economist's analysis is speculative, often elegant and pertinent to understanding problems of a general nature, but grossly abstract and inapplicable to practical management problems.

One field where cooperation between fishery biologists and economists would be rewarding is the harvesting of a system of interrelated species. In Chapter 3 we discussed how the question of prices and fishing costs of the various species is invoked when trying to optimize such a system. The maximization of quantitative yield would be inappropriate, and changes in relative prices might imply a complicated and not a priori obvious adjustment of fishing effort. As fisheries will be extended to more and more presently unexploited species, this approach will become increasingly relevant.

Another field for "joint ventures" would be the geographical distribution of fishing, e.g. the closing off of certain areas or "nursery grounds" where young, fast growing fish are predominant. As explained in Chapter 4, the age at fish should first be selected by the gear is a variable to be optimized. Usually this is thought of as being accomplished by varying mesh size, but a similar effect could possibly be obtained by closing certain areas to fishing. As the desirability of leaving young year classes unfished depends on fishing costs and optimal effort, so will even the closure of "nursery grounds".

The pulse fishing strategy considered in Chapter 5 is a novelty in the

discussion of fisheries management. Our conclusion was that it was not likely to be profitable with respect to the North Atlantic cod. This was concluded on the basis of highly aggregated data and plausible assumptions of fishing technology, but further empirical analysis of economic and biological data at the micro level would throw more light on this issue. It will be necessary to look into the cost, not only of fishing with various types of fleets, but of the whole fishing industry with respect to different processes. Empirical studies of the production function of fisheries proper, i.e. the possible relation of the availability coefficient to fishing effort and stock density (alias instantaneous returns to scale) and the relation of fishing effort in the economist's sense to fishing mortality, are pertinent to further study of the profitability of pulse fishing. An important aspect which we have not considered is pulse fishing of a system of species, interrelated or not.

Many questions raised by the extension of fishing limits call for an integrated biological/economic analysis. In cases where the fish migrate and are found within one nation's limits at a certain stage in their life, it is to a large extent possible to prohibit their migration to other's waters by a heavy fishing of the stock while within "the right" limits. At the same time, those who choose to do so may even hurt themselves, in case too few fish will be allowed to escape to the spawning grounds. As it might even be preferable to allow the fish to gain weight, there is an obvious room for bargaining among those who "share" a given stock in this way. Both economic and biological analysis will then be needed to evaluate different fishing strategies.

In short, a multidisciplinary approach is called for, and some already talk of "Fisheries Science". To quote a distinguished contributor to this field, economics of fisheries is "a fascinating subject where economists and biologists are clearly compliments and only talk as though they were substitutes when they misunderstand one another" (Turvey 1964).

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